(NASA-CP-2473) SPACECRAFT 2000 (NASA) 236 N88-10084
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NASA Conference Publication 2473

Spacecraft 2000

Proceedings of a workshop held at
NASA Lewis Research Center
Cleveland, Ohio
July 29–31, 1986

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1987

FOREWORD

The NASA Office of Aeronautics and Space Technology is currently investigating the potential for a new program initiative called Spacecraft 2000. The primary objective of the initiative is to identify and implement technology efforts required to develop a new generation of cost-effective spacecraft for the 21st century that meets NASA, military, and commercial needs and thereby maintains U.S. leadership and competitiveness. This is an ambitious undertaking that will require close collaboration of industry, universities, and government. This workshop was a first step, bringing together a wide range of spacecraft systems and subsystems technology experts from government and industry to define and prioritize the efforts that are most critical in spacecraft technology development and validation. The workshop attendance of 160 active participants from 42 organizations demonstrated the high level of interest and importance for this high-leverage area.

The Spacecraft 2000 Workshop organization was guided by an industry/government steering committee. Morning plenary and afternoon working group sessions were held each day. This document provides a record of all the slides used in the plenary sessions and the final reports from the nine technology working groups:

Spacecraft Systems
System Development
Structures and Materials
Thermal Control
Electrical Power
Telemetry, Tracking, and Control
Data Management
Propulsion
Attitude Control

A separate Executive Summary Report presenting an overview of the issues and recommendations of the working groups has already been distributed to all attendees.

I would like to take this opportunity to thank the joint industry/government steering committee, which was crucial in successfully guiding and formulating goals for Spacecraft 2000 and the workshop. The committee continues to provide enthusiastic leadership and guidance as the program evolves. The contribution of the Lewis Research Center Power Technology Division staff, under the leadership of Henry Brandhorst, Jr., in organizing and coordinating the workshop is also gratefully acknowledged.

J. Stuart Fordyce
Director of Aerospace Technology
NASA Lewis Research Center
Conference Chairman

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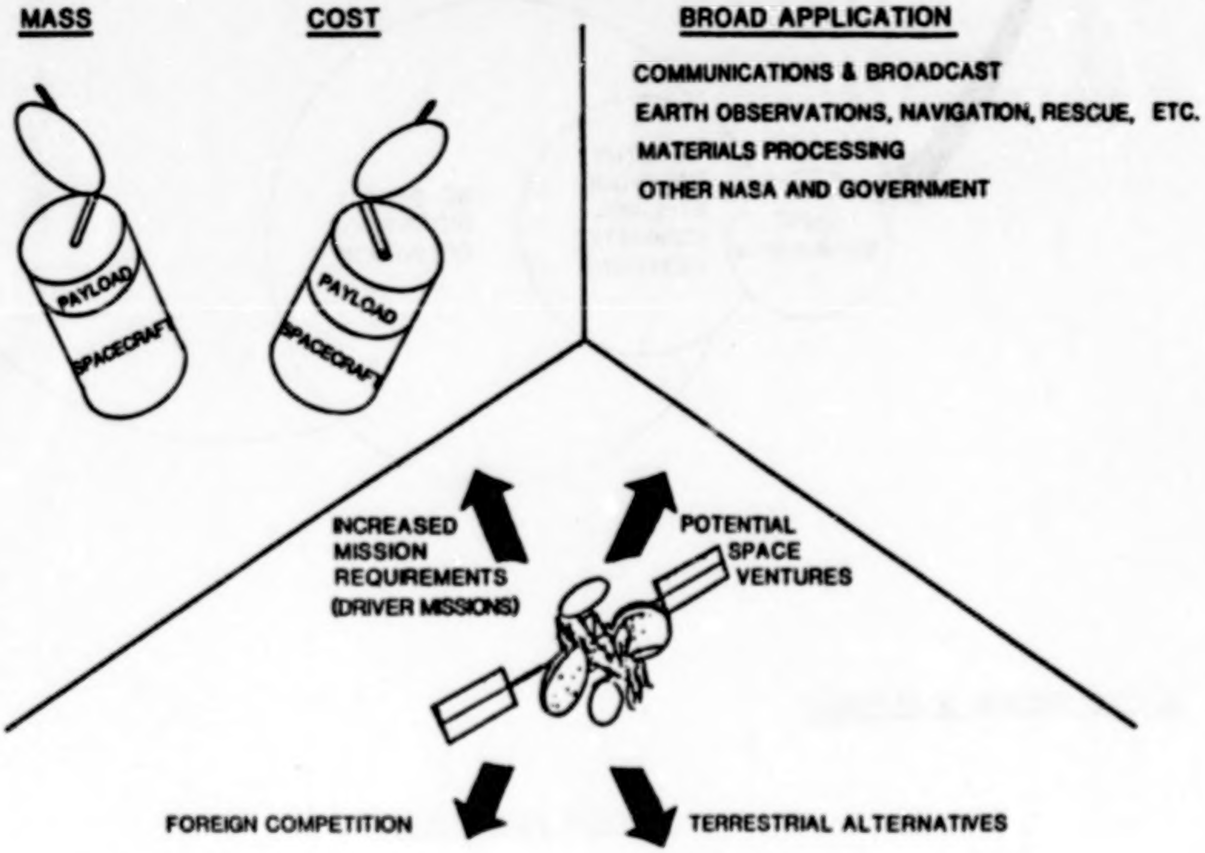
SPACECRAFT 2000 PROGRAM OVERVIEW

Robert Bercaw
NASA Lewis Research Center

WHY FOCUS ON THE SPACECRAFT?



MASS

COST

BROAD APPLICATION

COMMUNICATIONS & BROADCAST
EARTH OBSERVATIONS, NAVIGATION, RESCUE, ETC.
MATERIALS PROCESSING
OTHER NASA AND GOVERNMENT

INCREASED MISSION REQUIREMENTS (DRIVER MISSIONS)

POTENTIAL SPACE VENTURES

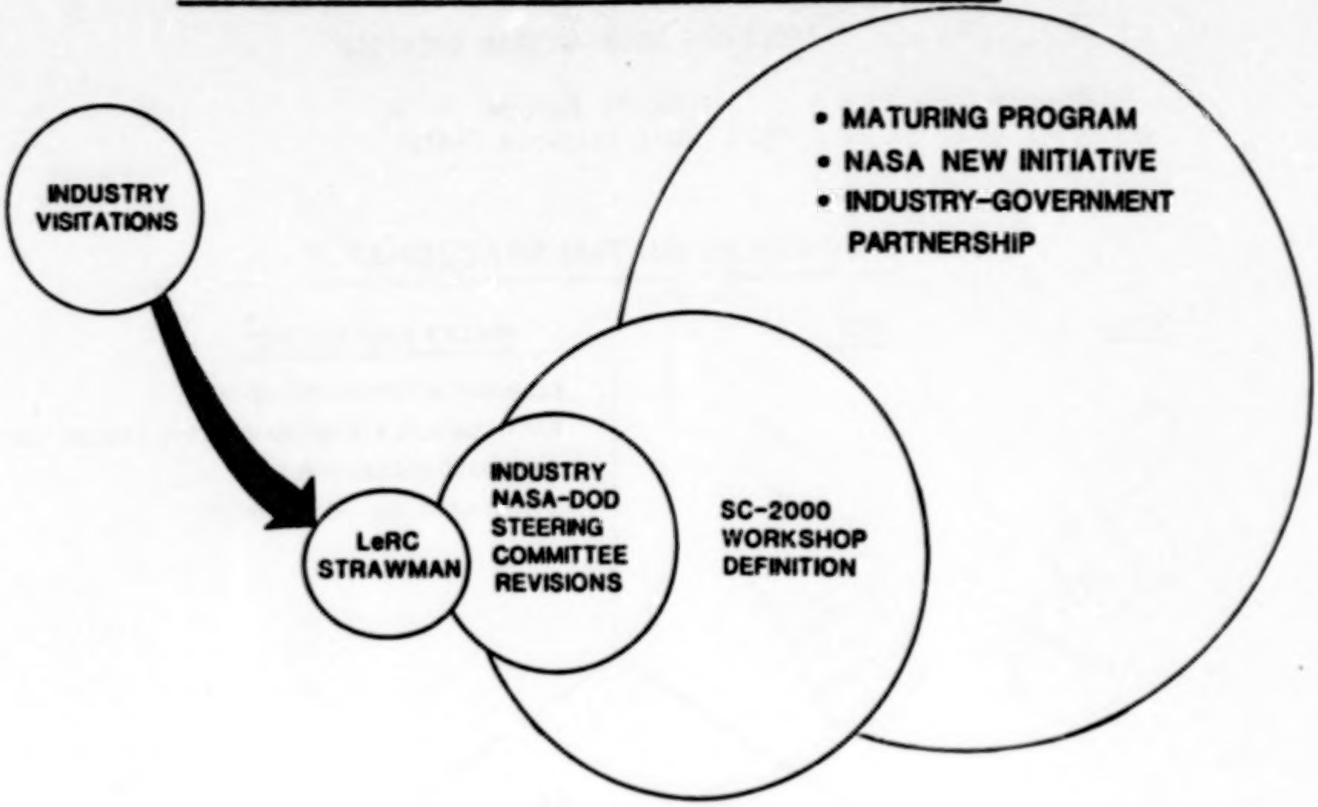
FOREIGN COMPETITION

TERRESTRIAL ALTERNATIVES

BARRIERS TO TECHNOLOGY DEVELOPMENT & UTILIZATION

DEFINITION	ADVOCACY	DEVELOPMENT	UTILIZATION
O SYSTEM COMPLEXITY	O LACK OF GOAL	O COMMUNICATION OF NEED	O TECHNICAL RISK
O DESIGN VARIETY	O ENABLING VS ENHANCING	O REQUIREMENT DEFINITION	O INCOMPATIBILITY WITH EXISTING DESIGNS
			O SPREAD OF TECH READINESS DATES

SPACECRAFT 2000 PROGRAM FORMULATION



INDUSTRY VISITATIONS

LeRC STRAWMAN

INDUSTRY NASA-DOD STEERING COMMITTEE REVISIONS

SC-2000 WORKSHOP DEFINITION

- MATURING PROGRAM
- NASA NEW INITIATIVE
- INDUSTRY-GOVERNMENT PARTNERSHIP

SC-2000 PROGRAM DEVELOPMENT

INDUSTRY VISITATIONS

- DISCUSSIONS WITH NINE COMPANIES
  - WIDE VARIETY OF SPECIFIC PROBLEMS
- AGREEMENT ON CRITICAL ISSUES
  - SPACECRAFT-RELATED COSTS
  - SPACECRAFT SUBSYSTEM WEIGHTS
  - SYSTEM LIFETIME & RELIABILITY
  - TECHNICAL RISKS
- CONSENSUS IS THAT A "SPACECRAFT 2000" TYPE PROGRAM IS IN THE NATIONAL INTEREST

S/C 2000 NASA/DOD/INDUSTRY STEERING COMMITTEE

MAJOR OBJECTIVES & SCOPE

PARTICIPATION: VOLUNTARY, FROM MAJOR SPACECRAFT VENDORS/SUBSYSTEMS SUPPLIERS/USERS ONE REPRESENTATIVE (OR ALTERNATE) PER ORGANIZATION

ROLE: RECOMMEND PROGRAM STRATEGY, OVERALL GOAL, TECHNOLOGY DEVELOPMENT/VERIFICATION PLAN. SUGGEST WAYS TO SERVE AND MEET NATIONAL NEEDS. ASSIST IN ADVOCACY OF POTENTIAL NEW INITIATIVES.

ADVISORY: PROVIDE ADVICE/GUIDANCE TO S/C 2000 WORKSHOP, AND ON PROJECTS OF MUTUAL INTEREST.

CONFIDENTIALITY: MAINTAIN AND PRESERVE CONFIDENTIALITY. RETAIN INTEGRITY OF INTERNAL PROGRAMS/PROCESSES OF PARTICIPATING ORGANIZATIONS

COORDINATION: COORDINATE OVERALL ACTIVITIES, FACILITATE TECHNOLOGY TRANSFER TO FLIGHT. EXCHANGE INFORMATION ON CONFIDENTIAL BASIS.

PROGRAM OBJECTIVE

TO IDENTIFY THE TECHNOLOGIES REQUIRED TO BUILD SPACECRAFT OF THE 21ST CENTURY, AND TO IMPLEMENT THE TECHNOLOGY PROGRAMS NEEDED TO ACHIEVE THEM.

INITIAL PROGRAM FOCUS

MASS LIMITED SYSTEM

- GEO SATELLITES
- GEO PLATFORMS
- POLAR PLATFORMS
- PLANETARY

SYSTEMS

- STRUCTURES
- BUS SYSTEMS
- INTEGRAL PROPULSION SYSTEMS

PROGRAM APPROACH

- O GOVERNMENT/INDUSTRY PARTNERSHIP
- O TOTAL SYSTEM APPROACH AT SPACECRAFT LEVEL
  - FOCUSED TECHNOLOGY
  - TECHNOLOGY READINESS DATE
- O ADDRESS ANCILLARY NONTECHNOLOGY ISSUES
  - DESIGN, DEVELOPMENT & TESTING
  - MANUFACTURING
  - OPERATIONS
- O VALIDATION USING TERRESTRIAL AND/OR IN-SPACE TEST BEDS
  - E.G., OAST OUTREACH/INREACH PROGRAM

KEY ISSUES

- O MAJOR TECHNICAL PROBLEMS IN CURRENT SPACECRAFT
- O MAJOR COST FACTORS IN CURRENT SPACECRAFT
- O ANTICIPATED SPACE INFRASTRUCTURE
- O MAJOR TECHNOLOGY REQUIREMENTS FOR FUTURE SPACECRAFT
- O ANTICIPATED DEMANDS FOR FUTURE TYPES OF SPACECRAFT
  - NASA
  - DOD
  - COMMERCIAL

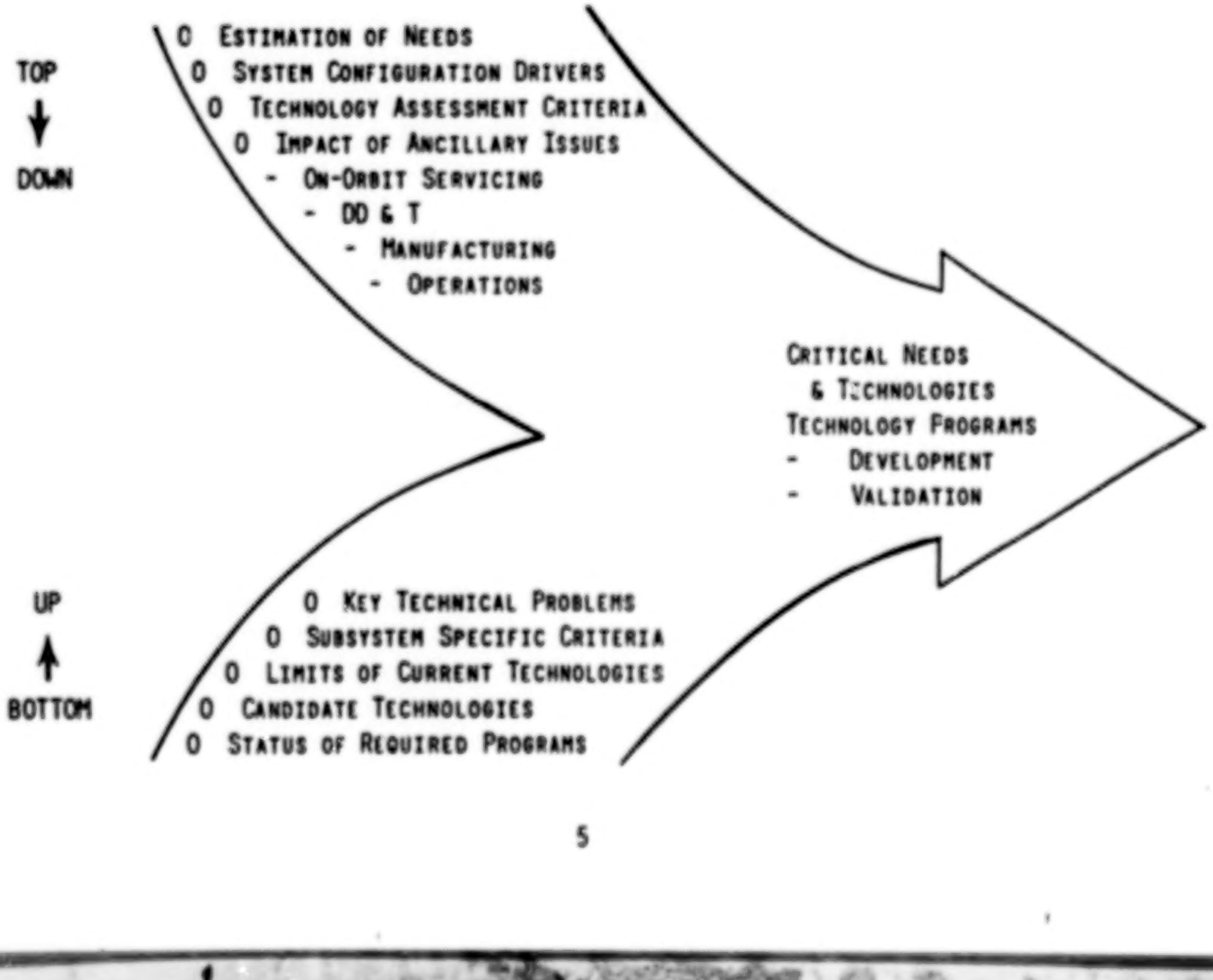
GOALS

- O TO IDENTIFY THE CRITICAL NEEDS AND TECHNOLOGIES FOR SPACECRAFT OF THE 21ST CENTURY.
- O TO RECOMMEND TECHNOLOGY DEVELOPMENT AND VALIDATION PROGRAMS, AND POSSIBLE GOVERNMENT/INDUSTRIAL ROLES AND PARTNERSHIPS.

OBJECTIVES

- O INCREASE AWARENESS AND EXCHANGE OF IDEAS AMONG PARTICIPANTS
- O HIGHLIGHT THE SPACECRAFT AS A FOCAL POINT FOR TECHNOLOGY
- O FACILITATE INDUSTRY-GOVERNMENT COORDINATION

WORKSHOP APPROACH



WORKSHOP OUTPUT

CONFERENCE PROCEEDINGS

- O PRESENTATIONS
- O WORKING GROUP REPORTS
  - CRITICAL TECHNOLOGIES
  - REQUIRED PROGRAMS VS TECHNOLOGY READINESS DATES
  - IMPACT OF SPACE INFRASTRUCTURE
  - VALIDATION REQUIREMENTS
  - COLLATERAL TECHNOLOGIES
  - ASSESSMENT OF ISSUES
  - RECOMMENDATIONS
- O CONFERENCE RECOMMENDATIONS (STEERING COMMITTEE)

BASIS FOR INITIAL PROGRAM PLAN

FOUNDATION FOR DESIGN & TECHNOLOGY TRADE STUDIES

WORKSHOP ORGANIZATION

LISA KOHOUT	GALE SUNDBERG
JIM KISH	HENRY CURTIS
KARL FAYMON	IRA MYERS

KAREN WESTER (CONFERENCE COORDINATOR)

MARJORIE FULLER

PAULA MITCHELL

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SPACE STATION PLATFORMS

Daniel Reid
General Electric Company

INTERNATIONAL SPACE STATION PLATFORMS

- o FIRST STEP TOWARD ROUTINE APPLICATION OF SPECIAL FEATURES
  - GROWTH STEP FROM MULTI-MISSION SPACECRAFT EXPERIENCE
- o EXPANDS TECHNOLOGY IN SEVERAL AREAS
  - POWER DISTRIBUTION
  - THERMAL CONTROL
  - DATA MANAGEMENT
- o GROWTH CAPABILITIES SCARRED INCLUDES
  - ROBOTIC SERVICING
  - PLATFORM GROWTH
  - ARTIFICIAL INTELLIGENCE FOR AUTONOMY

PLATFORM CONCEPTS REQUIRED

- o SUPPORT UNMANNED SCIENTIFIC RESEARCH & COMMERCIAL DEVELOPMENT
- o MULTIPLE PLATFORM TYPES

	RESEARCH	COMMERCIAL
- EARTH OBSERVATORIES	X	X
- ASTROPHYSICS OBSERVATORIES	X	
- MANUFACTURING FACILITIES	X	X
- LIFE SCIENCE LABORATORIES	X	

- o USER SUPPORT DEMANDS VERY DISTINCT
  - RESOURCE REQUIREMENTS
  - SPECIAL FEATURES

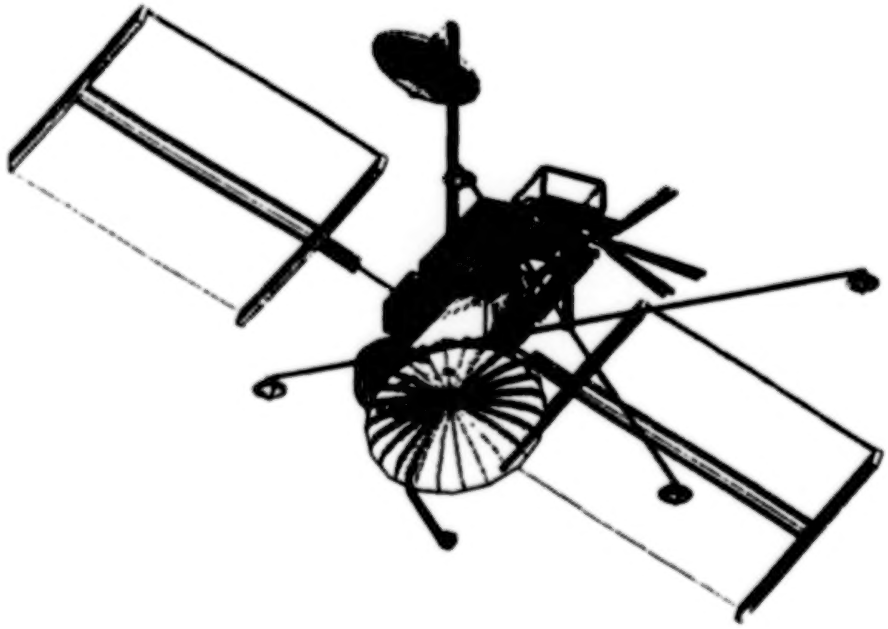
RESOURCE REQUIREMENTS

		SUBSYSTEM						
RESOURCE	**REQUIREMENT**	STRUC	THERM	ELECT	COMM	DATA	PROP	ATTIT
SIZE	EXTENSIVE MOUNTING AREA RQMTS OF MULTIPLE PAYLOAD SETS	X						X
HEAT	20-40 KILOWATT HEAT DISSIPATION SYSTEMS FOR PAYLOADS & SUBSYSTEM ELEMENTS	X	X					
POWER	GENERATION & DISTRIBUTION OF 20-40 KILOWATTS TO MULTIPLE USERS AS UTILITY SERVICE			X		X		
DATA	INDIVIDUAL INSTRUMENTS EXCEEDING 300 MEGABITS/SECOND WITH PAYLOAD SETS IN 450-500 RANGE				X	X		
COMPUTATION	ONBOARD DATA REDUCTION TO REDUCE TRANSMISSION AND GROUND LOADS					X		
POINTING	STABLE PRECISION POINTING OF LARGE FLEXIBLE PAYLOADS & STRUCTURES	X	X					X
ENVIRONMENT	MICRO-GRAVITY FOR MATERIAL PROCESSING AT 10 (-5) TO 10 (-9) G LEVELS	X					X	X

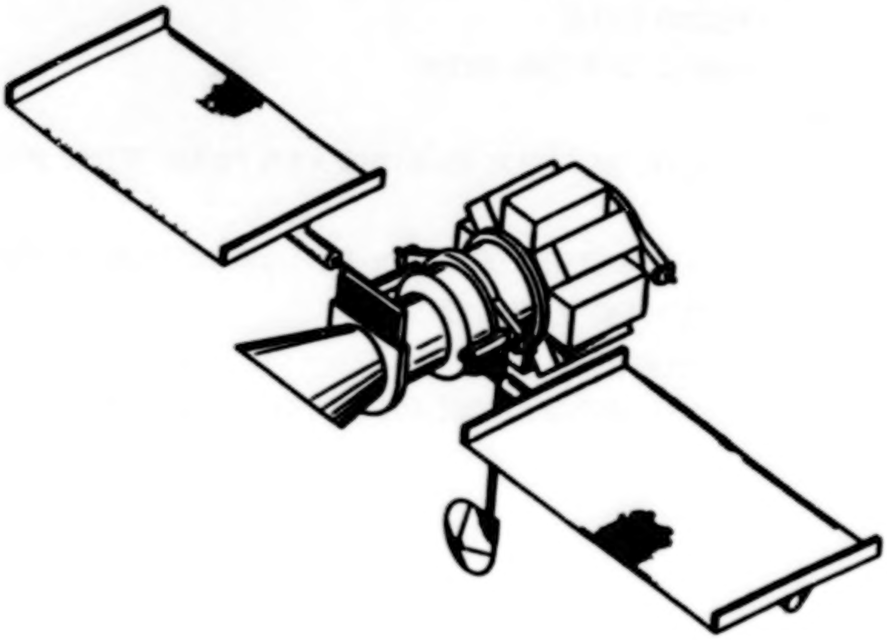
SPECIAL FEATURES

- SERVICING
  - EXTENDED MISSIONS THROUGH PREVENTATIVE MAINTENANCE & REPAIR
  - CHANGE-OUT OF PAYLOAD SET EXTENDING PLATFORM USE OVER MULTIPLE MISSION LIFES
  - ROBOTIC SERVICING SUPPORT
- GROWTH
  - ADAPTIVE SUBSYSTEMS AS REQUIREMENTS EXPAND BEYOND BASELINE
- MODULARITY
  - COMMON SUBSYSTEM SUPPORT OF DIFFERING MISSIONS TO REDUCE USER DEVELOPMENT REQUIREMENTS
- AUTONOMOUS OPERATIONS
  - REDUCED GROUND SUPPORT FOR LIFE CYCLE COST CONTROL

SPACE STATION PLATFORM
POLAR CONFIGURATION



SPACE STATION PLATFORM
SIRTF CONFIGURATION



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MILITARY NEEDS AND FORECAST II

Alan Goldstayn
U.S. Air Force

OBJECTIVE

- PRODUCE A LIST OF MAJOR WAR-FIGHTING/WAR-SUPPORTING CAPABILITIES THAT COULD BE REALIZED BY:
  - EXPLOITING EMERGING/ANTICIPATED TECHNOLOGIES
  - INCORPORATING THE TECHNOLOGIES INTO INNOVATIVE SYSTEMS CONCEPTS
- SUBMIT TO AIR FORCE CORPORATE REVIEW FOR SELECTION OF CAPABILITIES FOR FURTHER DEVELOPMENT

TASKING

12 JUN 85 LETTER FROM SECRETARY ORR AND GENERAL GABRIEL

"ONE OF THIS NATION'S FUNDAMENTAL STRENGTHS IS ITS ABILITY TO TURN TECHNOLOGICAL OPPORTUNITIES INTO SUPERIOR WEAPONS SYSTEMS ..."

"WE NEED TO BREAK AWAY FROM CONVENTIONAL THINKING, LOOK AT WHAT IS TECHNOLOGICALLY POSSIBLE ..."

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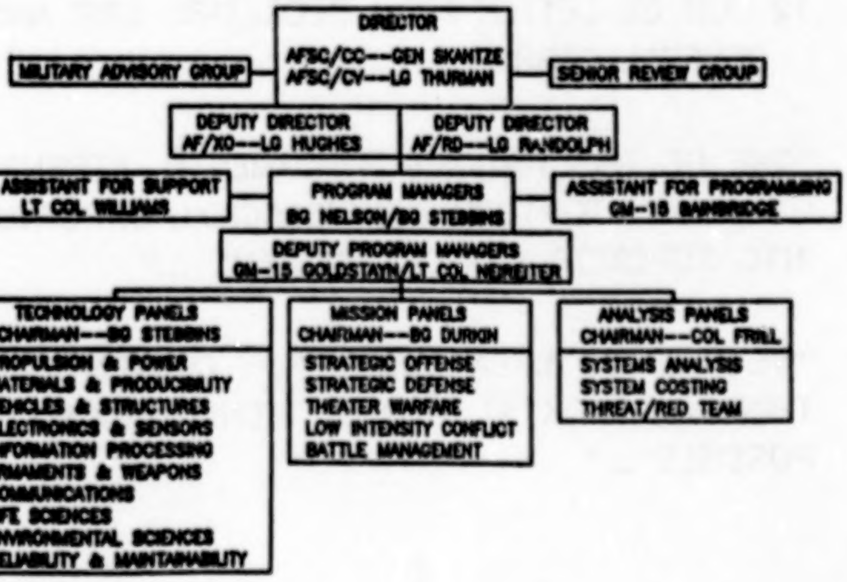
PROJECT FORECAST II

- o SPONSORED BY SAF & CSAF
- o 10–20 YEAR TECHNOLOGY PUSHES
- o IN-HOUSE AF, ASSISTED BY INDUSTRY & ACADEMIA
- o SEEKING BROAD CONSENSUS
- o PRESENTED TO CORPORATE AF LEADERSHIP
- o 175 AIR FORCE MILITARY AND CIVILIAN PERSONNEL
  - -HAND-PICKED FROM MAJCOMS AND LABS
- o SPENT 6 MONTHS CREATING 2,000 IDEAS
  - -EXPOSED THE BEST IDEAS TO SOME OF THE FINEST MINDS IN THE COUNTRY
- o SELECTED 70 TECHNOLOGIES AND SYSTEMS INITIATIVES



DIRECTOR
AFSC/CC---GEN SKANTZE
AFSC/CY---LG THURMAN

MILITARY ADVISORY GROUP

SENIOR REVIEW GROUP

DEPUTY DIRECTOR
AF/XO---LG HUGHES

DEPUTY DIRECTOR
AF/RD---LG RANDOLPH

ASSISTANT FOR SUPPORT
LT COL WILLIAMS

PROGRAM MANAGERS
BG NELSON/BG STEBBINS

ASSISTANT FOR PROGRAMMING
GM-15 BAINBRIDGE

DEPUTY PROGRAM MANAGERS
GM-15 GOLDSTAYN/LT COL NEIREITER

TECHNOLOGY PANELS
CHAIRMAN---BG STEBBINS
PROPULSION & POWER
MATERIALS & PRODUCIBILITY
VEHICLES & STRUCTURES
ELECTRONICS & SENSORS
INFORMATION PROCESSING
ARMAMENTS & WEAPONS
COMMUNICATIONS
LIFE SCIENCES
ENVIRONMENTAL SCIENCES
RELIABILITY & MAINTAINABILITY

MISSION PANELS
CHAIRMAN---BG DURKIN
STRATEGIC OFFENSE
STRATEGIC DEFENSE
THEATER WARFARE
LOW INTENSITY CONFLICT
BATTLE MANAGEMENT

ANALYSIS PANELS
CHAIRMAN---COL FRILL
SYSTEMS ANALYSIS
SYSTEM COSTING
THREAT/RED TEAM

MILITARY ADVISORY GROUP

- VICE COMMANDERS OF: AFLC, ATC, MAC PACAF, SAC, SPACECMD, TAC, USAFE
- COMMANDERS OF: AAC, AFCC, AU, DIA, ESC, NMC
- HQ USAF: DCS/LE, DCS/PR, AF/IN, AF/SA
- OJCS: VDJS

PROCESS

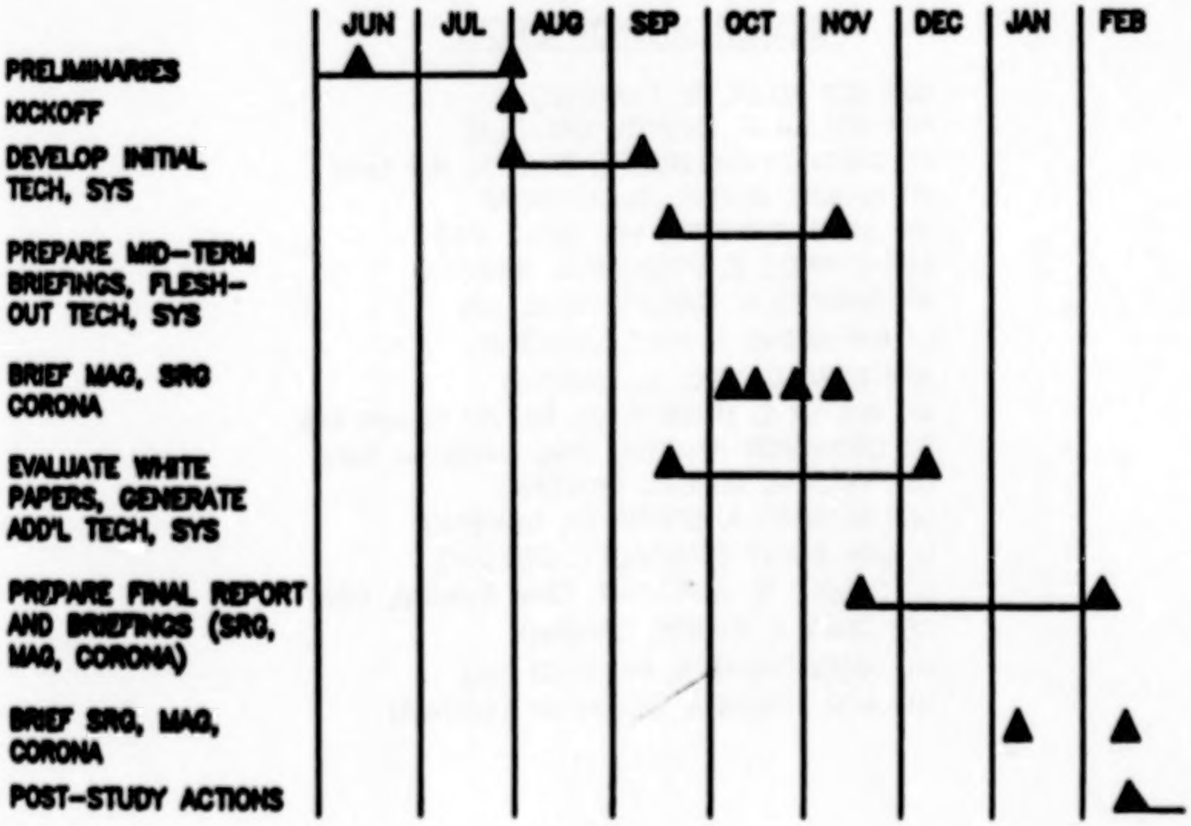
SENIOR REVIEW GROUP

GEN LEW ALLEN, Jr, USAF(Ret)
GEN WILLIAM W. MOMYER, USAF(Ret)
DR SOLOMON BUCHSBAUM, Exec VP, Bell Labs
DR EUGENE COVERT, Chmn, AFSAB
MR JULIAN DAVIDSON, VP, Chmn, AFSB
GEN RUSSELL E. DOUGHERTY, USAF(Ret)
MR CHARLES A. FOWLER, Chmn, DSB
LT GEN GLENN A. KENT, USAF(Ret)
ADM ISSAC C. KIDD, Jr, USN(Ret)
MR WALTER E. MORROW, Jr, Dir, MIT Lincoln Lab
DR EBERHARDT RECHTIN, Pres, Aerospace Corp
GEN FELIX M. ROGERS, USAF(Ret)
GEN BERNARD A. SCHRIEVER, USAF(Ret)
LT GEN BRENT SCOWCROFT, USAF(Ret)
DR HAROLD W. SORENSON, Chief Scientist, USAF
GEN DONN A. STARRY, USA(Ret)
DR JAMES THOMSON, VP, RAND Corp
MAJ GEN JASPER A. WELCH, Jr, USAF(Ret)

PANEL TASKS

- TECHNOLOGY PANEL GROUP
  - ASSESS TECHNOLOGY BASE, TRENDS, RISKS
  - IDENTIFY EMERGING TECHNOLOGIES
- MISSION PANEL GROUP
  - IDENTIFY CAPABILITIES NEEDED BY USING COMMANDS
  - EVALUATE UTILITY OF TECHNOLOGIES AND SYSTEMS IDENTIFIED
- ANALYSIS PANEL GROUP
  - ASSESS THE THREAT AND PERFORM "RED TEAMING"
  - ANALYZE SYSTEMS IDENTIFIED (COMPARE AGAINST ALTERNATIVES)
  - DEVELOP AND MONITOR THE STUDY PROCESS

SCHEDULE



HYPERVELOCITY VEHICLES

DESCRIPTION

HYPERSONIC VEHICLES FOR SUB-ORBITAL AND EARTH-TO-ORBIT AND RETURN OPS

PAYOFFS

- ROUTINE, AFFORDABLE SPACE OPS
- ICBM RESPONSE TIME WITH MANNED AIRCRAFT FLEXIBILITY
- QUICK-REACTION SURVEILLANCE

BOOST GLIDE VEHICLE

DESCRIPTION

TRANSATMOSPHERIC VEHICLE BOOSTED TO HYPERSONIC VELOCITIES CAPABLE OF MANEUVERING IN FLIGHT

PAYOFFS

- RAPID REACTION CAPABILITY WITH SYSTEM FREED FROM BALLISTIC CONSTRAINTS
- MANEUVERABILITY TO EXPAND OPERATIONAL ENVELOPE
- MATERIAL CONSTRUCTION TO WITHSTAND HIGH TEMPERATURE AND STRUCTURAL LOADING

MANNED SPACE STATION

DESCRIPTION

CONTINUOUSLY MANNED, MODULARLY CONSTRUCTED, MULTIPURPOSE SPACE FACILITY FOR MAINTENANCE, STORAGE, DOCKING, AND REPAIR OF SPACE ASSETS. FACILITY WILL BE IN A SURVEILLANCE SATELLITE-TYPE ORBIT POWERED BY SOLAR CELL GENERATOR OR NUCLEAR SOURCE.

PAYOFFS

MAIN OPERATING BASE FOR SPACE SORTIES

SATELLITE OR OTHER SPACE VEHICLE REPAIR FACILITY

DATA PROCESSING SITE FOR SURVEILLANCE SATELLITES

ALTERNATE COMMAND POST

ADVANCED HEAVY LIFT SPACE VEHICLE

DESCRIPTION

A REUSABLE LAUNCH VEHICLE WHICH TRANSPORTS PAYLOADS RANGING FROM 150,000 TO 300,000 POUNDS FROM EARTH TO ORBIT

PAYOFFS

MORE FLEXIBILITY IN SPACE TRANSPORTATION

TEN FOLD DECREASE IN CURRENT COST PER POUND TO ORBIT PAYLOADS

ENABLES SPACE-BASED BATTLE MANAGEMENT

CHEMICALLY-BOUND, EXCITED STATE MATERIALS

DESCRIPTION

NEW FAMILY OF HIGHLY ENERGETIC MATERIALS THAT PROMISES RADICALLY INCREASED PROPULSIVE/EXPLOSIVE CAPABILITIES

ENABLED BY:
- NEW THEORIES -- SUPER COMPUTER MODELING
- NEW DATA -- LASER DIAGNOSTICS

PAYOFFS

- POTENTIAL REVOLUTION IN AEROSPACE PROPULSION
  - AT LEAST 10X REDUCTION IN COST TO ORBIT
  - AT LEAST 10X INCREASE IN AIRCRAFT CAPABILITY (RANGE, ETC.)
- ALL-ASPECT LAUNCH FOR ROCKETS
- COMPACT HYPERSONIC VELOCITY VEHICLES -- ROUTINE OPERATIONS FROM CONVENTIONAL RUNWAYS
- NEW HIGH EXPLOSIVES
- NEW ENERGY SOURCES

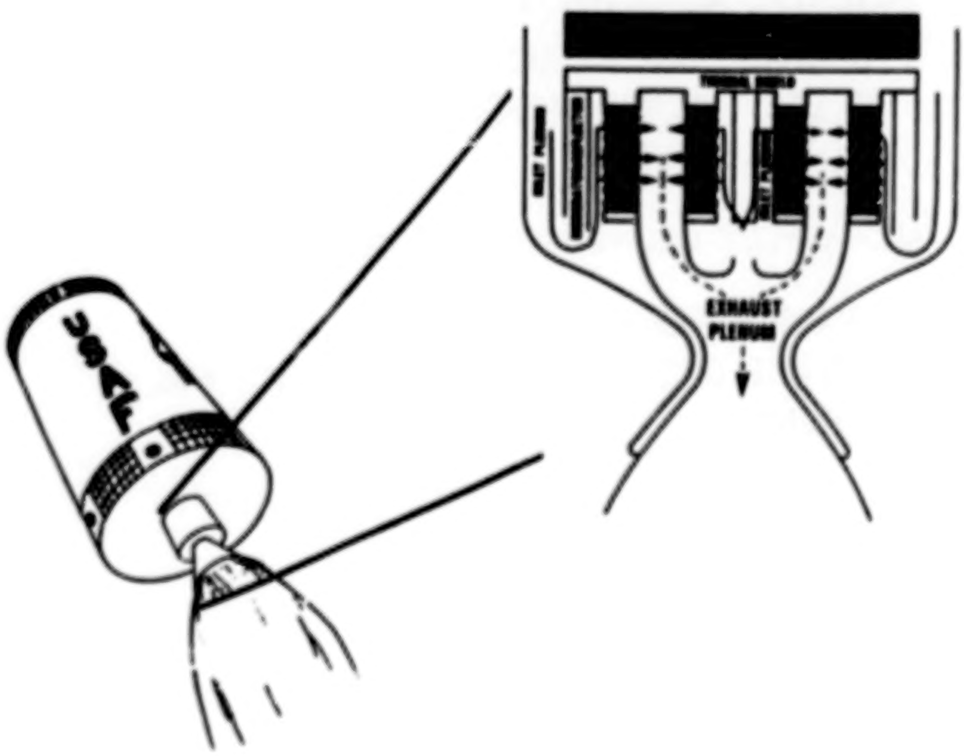
SAFE, COMPACT, NUCLEAR PROPULSION IN SPACE

DESCRIPTION

FRESH APPROACH -- HYDROGEN PROPELLANT HEATED BY HOT, CERAMIC-CONFINED, NUCLEAR FUEL PELLETS

PAYOFFS

- MULTIPLE OTV OPERATIONS FOR GIVEN FUEL LOAD
- VERY SIMPLE OPERATION -- LOW RECURRING COSTS
- OIL-BARREL SIZE -- 50,000 LBS THRUST
- SAFE -- INERT UNTIL READY FOR OPERATION IN SPACE. CLEAN DISPOSAL AFTER DEPLETION
- CLEAN EXHAUST -- NO NUCLEAR PRODUCTS



ANTI-PROTON TECHNOLOGY

DESCRIPTION

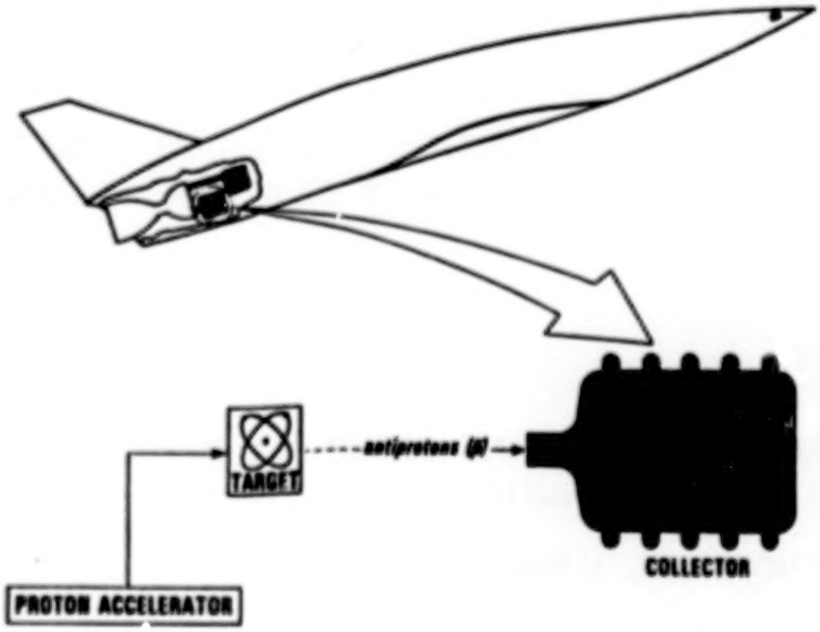
JOIN PROTONS & ANTI–PROTONS TO CREATE ENORMOUS ENERGY SOURCES

PAYOFF

FUEL WEIGHT ALMOST NIL FOR MULTIPLE OPS IN SPACE

GREAT MILITARY POTENTIAL

BREAKTHROUGH IN SPACE TRAVEL



DISTRIBUTED SPARSE ARRAY OF SPACECRAFT

DESCRIPTION

SPARSE PHASED ARRAY IN SPACE FOR RADAR, COMM, & SIGINT USING UNCONNECTED, IDENTICAL ELEMENTS SPREAD OVER A LARGE AREA

PAYOFFS

- SURVIVABLE CONSTELLATION WITH NO CRITICAL NODES
- GROWTH POTENTIAL WITH PERFORMANCE/COST TRADEOFFS
- LOWER TOTAL SYSTEM COST POTENTIAL

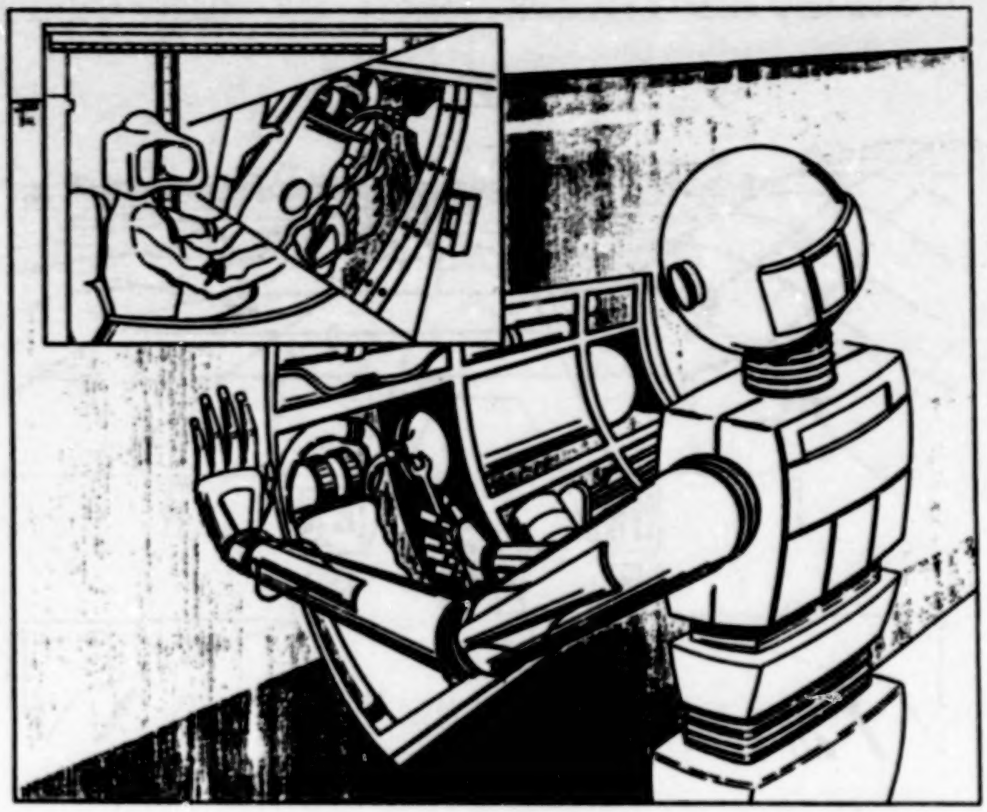
TELEPRESENCE/ADAPTIVE ROBOTICS

DESCRIPTION

RELATIVELY UNSOPHISTICATED ROBOTS THAT PERMIT MAN TO VIEW AND MANIPULATE OBJECTS FROM REMOTE LOCATIONS

PAYOFFS

- RUNWAY AND AIRCRAFT REPAIR AND REFURBISHMENT IN CBR ENVIRONMENT
- REMOTE SITE MANNING
- SCALE UP FOR HEAVY LIFT AND CONSTRUCTION, ETC
- SCALE DOWN FOR ELECTRONIC DEVICE REPAIR, ETC



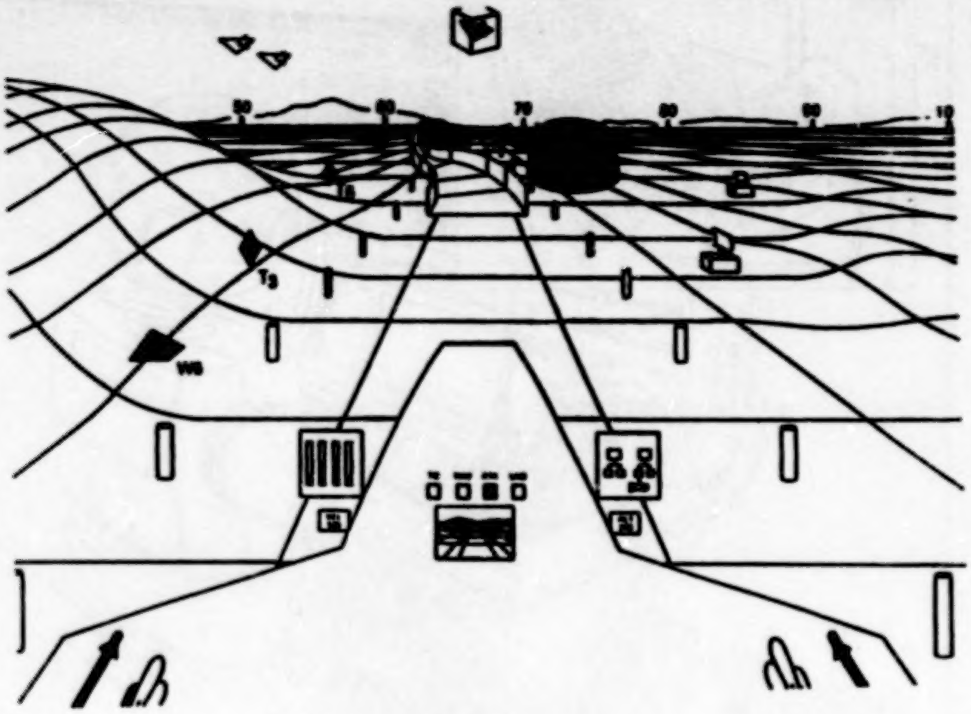
SUPER COCKPIT

DESCRIPTION

FULL INTEGRATION OF 3-D NATURAL DISPLAY OF SENSORS, FLIGHT CONTROL, AND FIRE-CONTROL SYSTEMS

PAYOFFS

- o ALL-WEATHER/NIGHT OPS
- o ALL AXES SITUATIONAL AWARENESS
  - oo INCREASED SURVIVABILITY AND KILL EFFECTIVENESS
- o REDUCED PILOT WORKLOAD



INTEGRATED PHOTONICS

DESCRIPTION

INTEGRATE OPTICAL SYSTEMS DEVICES TO ESSENTIALLY REPLACE ELECTRONS WITH PHOTONS IN A VARIETY OF APPLICATIONS

PAYOFFS

- o ALL-PHOTONIC SYSTEMS -- AIRCRAFT, SPACECRAFT, 21ST CENTURY BATTLE MANAGEMENT, ETC
  - oo EMP HARDENED/RADIATION HARDENED
  - oo EXTREMELY DIFFICULT TO DETECT AND JAM
- o AT LEAST 10,000X INCREASE IN INFORMATION TRANSFER SPEED, 100X IN PROCESSING SPEED

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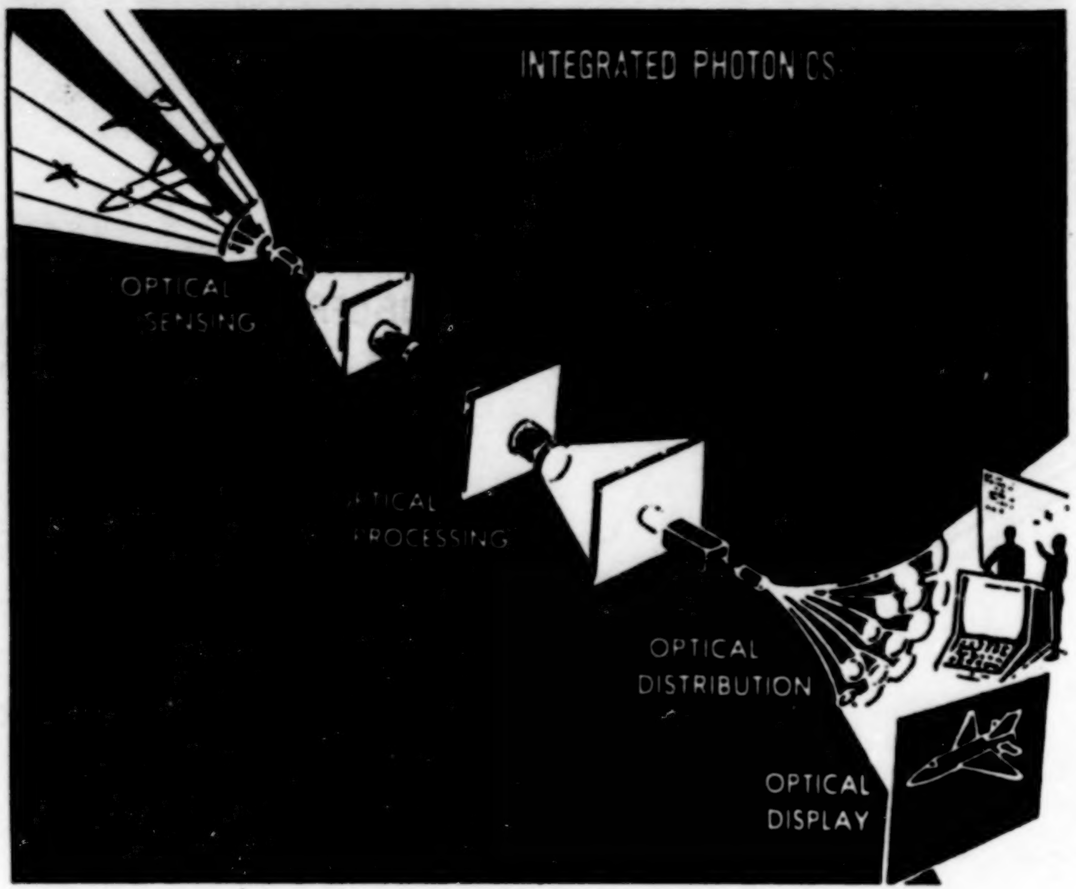


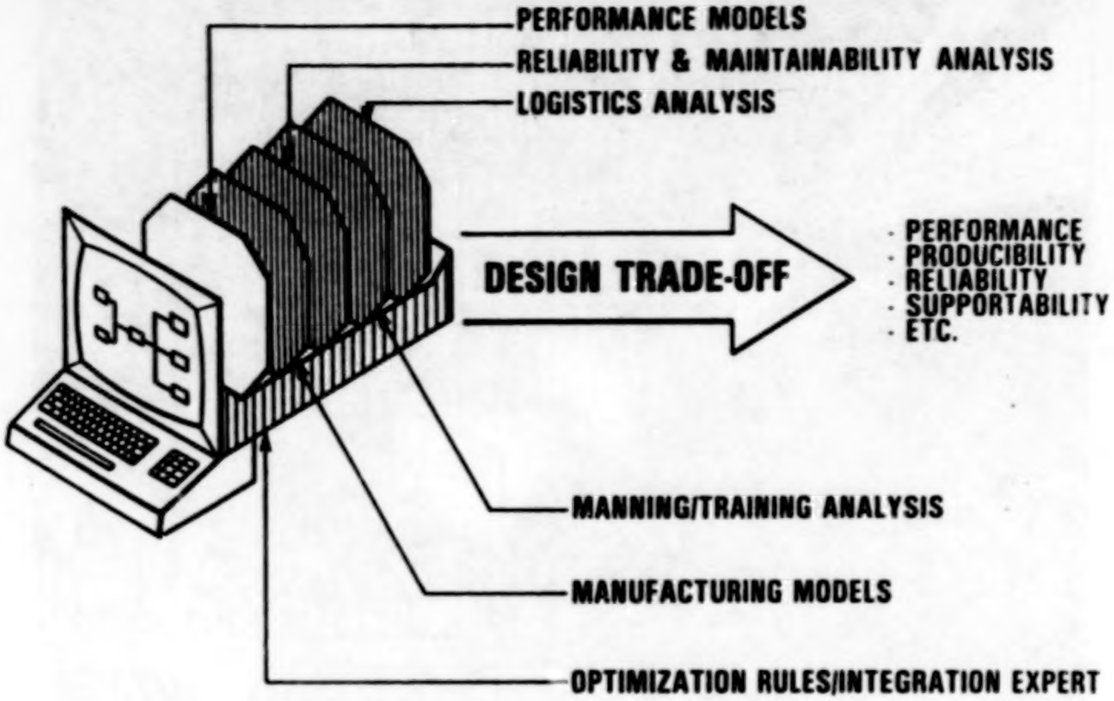
UNIFIED LIFE CYCLE ENGINEERING

DESCRIPTION

EXPANDED & INTEGRATED COMPUTER MODELS OF PERFORMANCE, MANUFACTURING & SUPPORTABILITY

PAYOFF

TRADEOFFS DURING DESIGN PHASE. BETTER SYSTEMS THAT ARE PRODUCIBLE, AFFORDABLE & SUPPORTABLE



IMPLEMENTATION PLAN

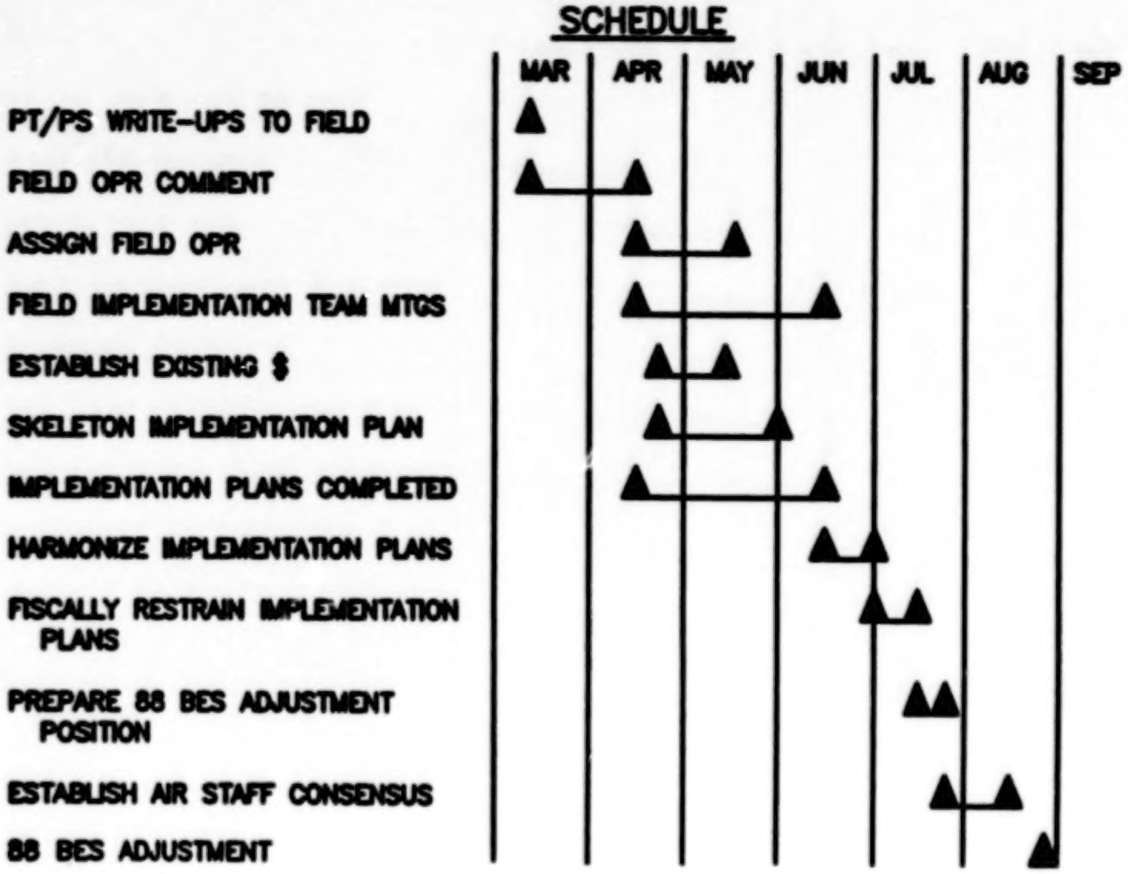
IMPLEMENTATION OBJECTIVES

- APPROVED INVESTMENT STRATEGY FOR FORECAST II INITIATIVES
  - ADVOCATED BY THE MAJCOMS AND AIR STAFF
  - "HARMONIZED" WITH OTHER SERVICES, DOD, & AGENCIES

- LEVERAGING OF INDUSTRY AND ACADEMIA
  - FOCUSING OF IR&D
  - GRANT RESEARCH

- PUBLIC AWARENESS AND SUPPORT
  - TRADE PUBLICATIONS
  - GENERAL MEDIA SOURCES

PROJECT PLANS



SUMMARY

FORECAST II HAS ACCOMPLISHED ITS OBJECTIVES OF IDENTIFYING HIGH LEVERAGE TECHNOLOGIES FOR CORPORATE AF REVIEW

IMPLEMENTATION IS UNDERWAY WITH EMPHASIS ON RESTRUCTURING EXISTING PROGRAMS AND PROGRAMMING RESOURCES IN THE FY88 BES/FY89 POM

MANY JOINT SERVICE/AGENCY OPPORTUNITIES EXIST

N88
10088
UNCLAS

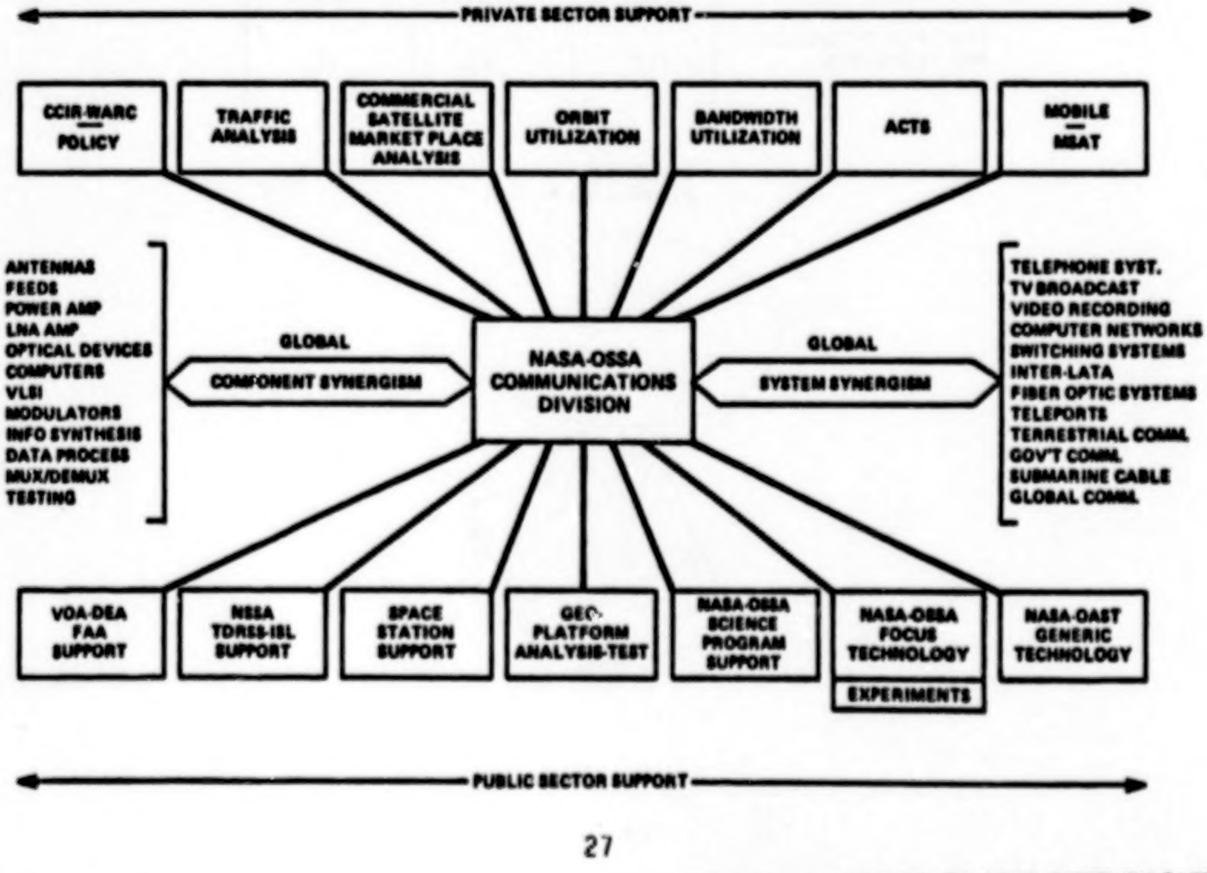
N88-10088

COMMUNICATION SATELLITE TECHNOLOGY TRENDS

Louis Cuccia
NASA Headquarters

A CHRONOLOGY OF SPACE-EARTH INTERCONNECTIVITY

- o THE 1960's- INTERNATIONAL COMMUNICATIONS
- o THE 1970's- INTERNATIONAL AND NATIONAL DOMESTIC COMMUNICATIONS
- o THE 1980's- INTERNATIONAL, NATIONAL, AND REGIONAL SATELLITE COMMUNICATIONS
- o THE 1990's- GLOBAL INTERCONNECTIVITY BY LASER LINKS INTERCONNECTING SATELLITES IN THE ORBITAL ARC
- o 2000+ SPACE NETWORK INTERCONNECTIVITY FOR EARTH, LOW EARTH ORBIT, AND GEOSTATIONARY ORBIT COMMUNICATION SYSTEMS



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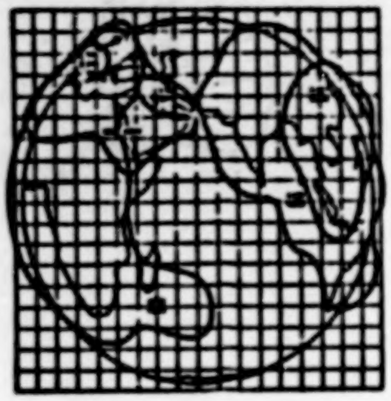
PERSPECTIVE ON THE 1960'S- INTERNATIONAL COMMUNICATIONS

	INTELSAT I	INTELSAT II	INTELSAT III
YEAR OF FIRST LAUNCH	1965	1967	1968
HEIGHT (CM)	60	67	104
WEIGHT IN ORBIT (KG)	38	86	152
ELECTRICAL POWER (KW)	0.04	0.075	0.120
CAPACITY (TELEPHONE CIRCUITS)	240	240	1,200
DESIGN LIFETIME (YEARS)	1.5	3	5
INVESTMENT COST PER CIRCUIT YEAR	$32,500	$11,400	$2,000
COST PER S/C ON ORBIT (MILLIONS OF $)	11.7	8.2	12.2

30 METER
STANDARD A

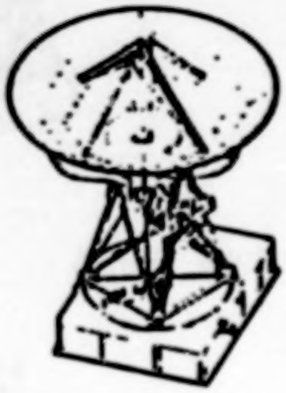
PERSPECTIVE ON THE 1970'S

INTERNATIONAL SYSTEMS

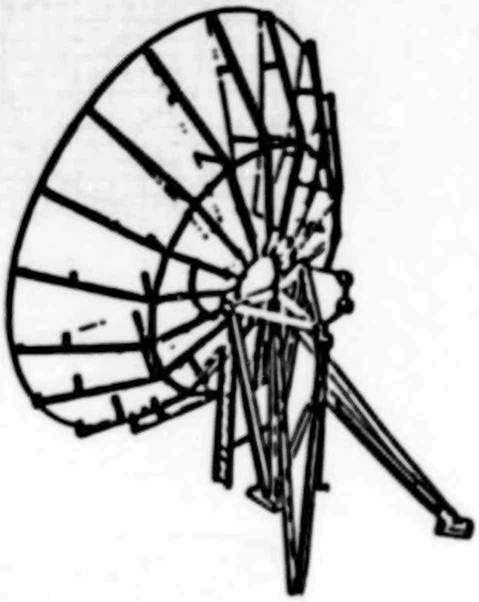


INTELSAT V Indian Ocean Coverage

30 METER
STANDARD A



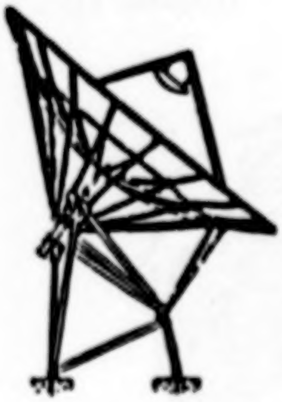
10-13 METER
STANDARD B



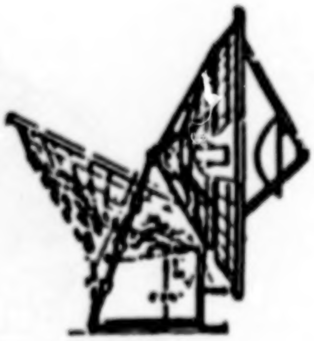
NATIONAL SYSTEMS

GROUP OF FREQUENCIES F_1 REUSED

9-10 METER
CA-TV



4.5 METER
CA-TV



PERSPECTIVE ON THE 1980'S

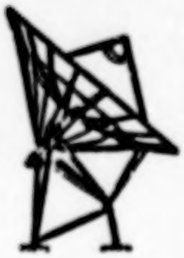
INTERNATIONAL SYSTEMS

30 METER
STANDARD A

10-13 METER
STANDARD B

NATIONAL SYSTEMS

9-10 METER
CA-TV



4.5 METER
CA-TV

REGIONAL SYSTEMS

Coverage of Arabsat and Eutelsat

3 METER
MEDIA
DISTRIBUTION

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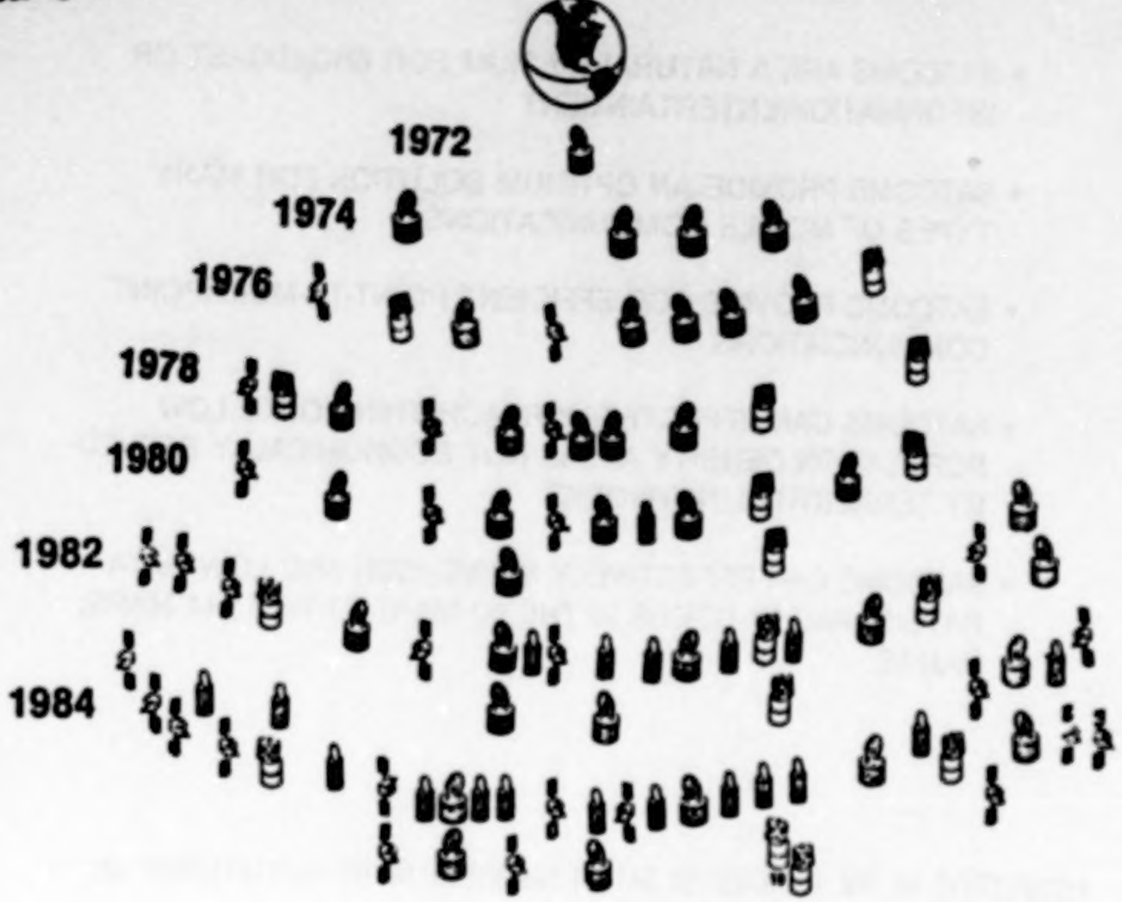
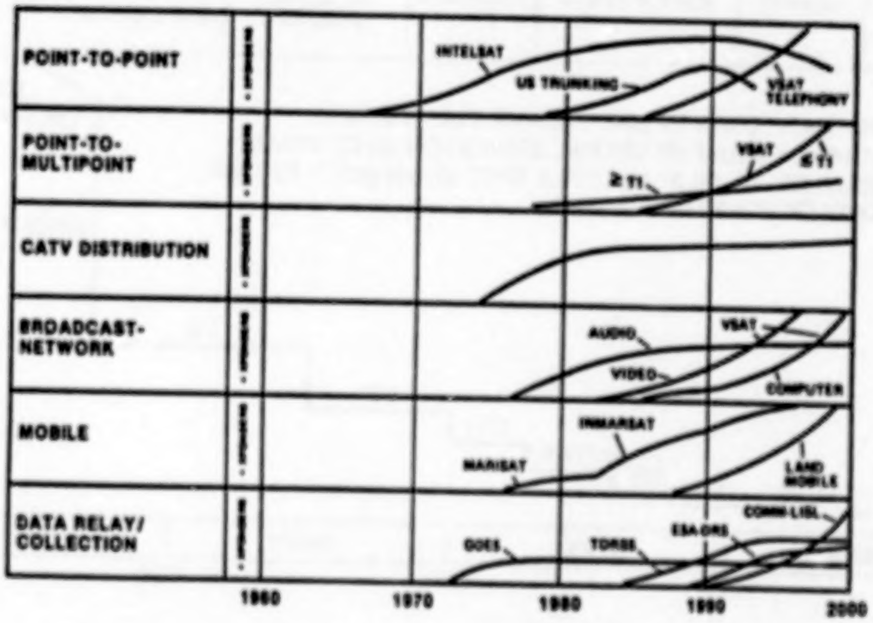
NO. AMERICAN DOMSATS IN GEOSTATIONARY ORBIT



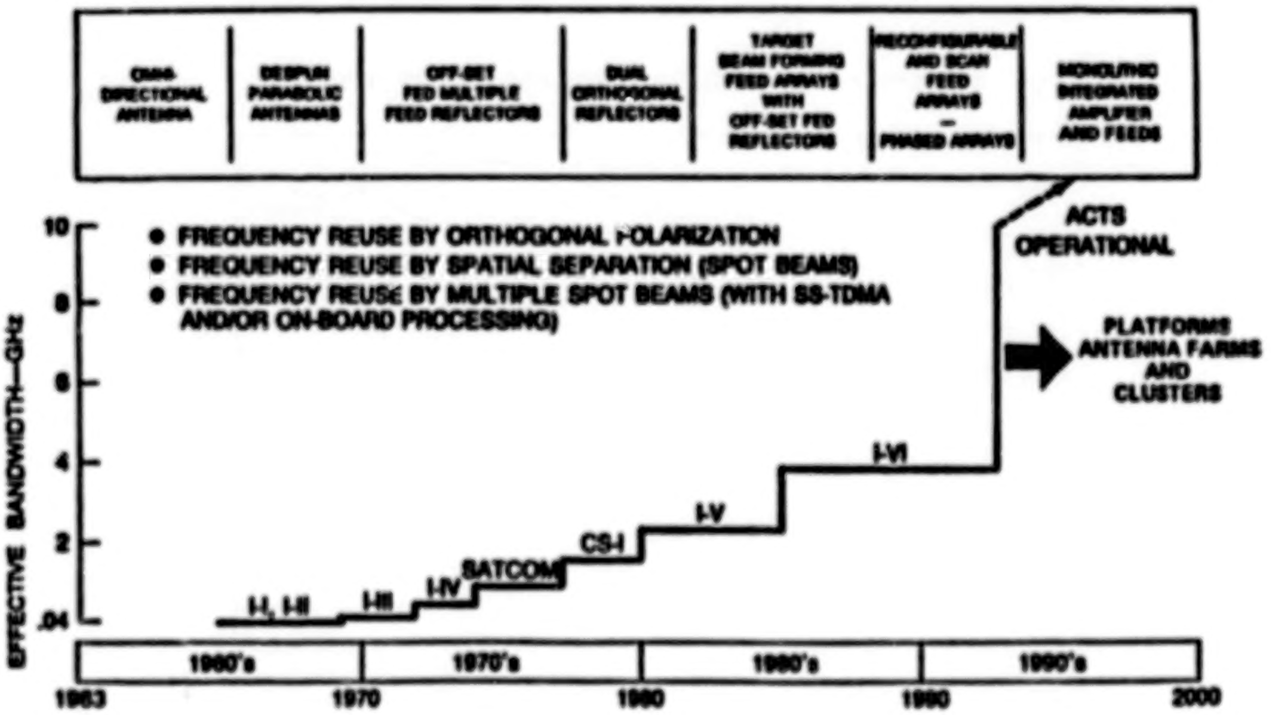
COMMUNICATIONS SATELLITE TRENDS AND OPPORTUNITIES



FUTURE ROLES OF COMMUNICATIONS SATELLITES

- SATCOMS ARE A NATURAL MEDIUM FOR BROADCAST OR INFORMATION/ENTERTAINMENT
- SATCOMS PROVIDE AN OPTIMUM SOLUTION FOR MANY TYPES OF MOBILE COMMUNICATIONS
- SATCOMS PROVIDE FOR EFFICIENT POINT-TO-MULTIPOINT COMMUNCIATIONS
- SATCOMS CAN EFFECTIVELY REACH THIN ROUTE LOW POPULATION DENSITY AREAS NOT ECONOMICALLY SERVED BY TERRESTRIAL NETWORKS
- SATCOMS CAN EFFECTIVELY SERVE ISDN AND LOW DATA RATE/CAPACITY USERS IN THE 50 KBPS TO T1 (1.544 MBPS) RANGE

PERSPECTIVE ON THE INCREASE IN SATCOM BANDWIDTH IN THE GEOSTATIONARY ARC



NASA PROGRAMS IN ADVANCED TECHNOLOGY AND SPACE SYSTEM DEVELOPMENT

- ADVANCED COMMUNICATIONS TECHNOLOGY SATELLITE (ACTS)
- MOBILE SATELLITE SYSTEM MSAT
- SHUTTLE-ACTS LASER LINK
- SPACE STATION COMMUNICATIONS/ANTENNA TEST RANGE
- GEOSTATIONARY COMMUNICATIONS PLATFORM

THE ENABLING TECHNOLOGIES FOR SPACE SWITCHING CENTERS AND GEOSTATIONARY INTERCONNECTION

TECHNOLOGY	WHERE IN DEVELOPMENT	TIME FRAME
• NARROW BAND (≳5 KBPS) SUBSCRIBER COMMUNICATION	MOBILE SATELLITE	1988 ON
• WIDE BAND (56 KBPS) TRUNK SWITCHING	ACTS SATELLITE	1990
• INTERSATELLITE LINK	ACTS - SHUTTLE EXPERIMENT	1990
• SUPER COMPUTER FOR SPACE	IN DEVELOPMENT IN PRESENT MARKET PLACE	1995

ACTS SYSTEM

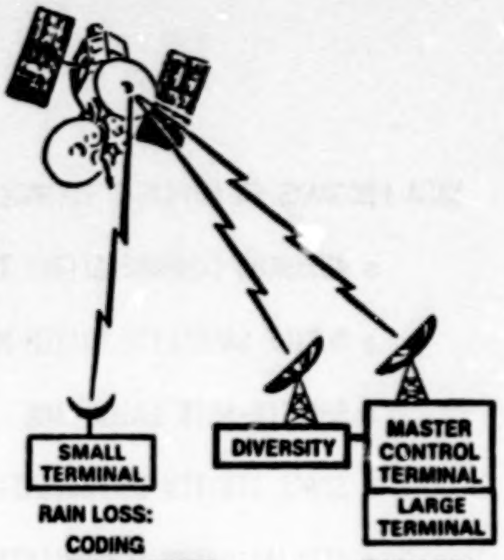
PRIMARY OBJECTIVES:

TO PROVE THE FEASIBILITY OF ADVANCED COMMUNICATIONS SATELLITE TECHNOLOGIES IN THE ENVIRONMENT OF SPACE AND REPRESENTATIVE EARTH ATMOSPHERIC CONDITIONS:

- FIXED AND SCANNING SPOT BEAMS
- FREQUENCY REUSE
- BEAM INTERCONNECTING VIA SATELLITE SWITCHING
- SYSTEM NETWORKING
- RAIN COMPENSATION TECHNIQUES

SECONDARY OBJECTIVE:

OPTICAL INTER-SATELLITE LINK RESEARCH FACILITY



SMALL TERMINAL

DIVERSITY

MASTER CONTROL TERMINAL

LARGE TERMINAL

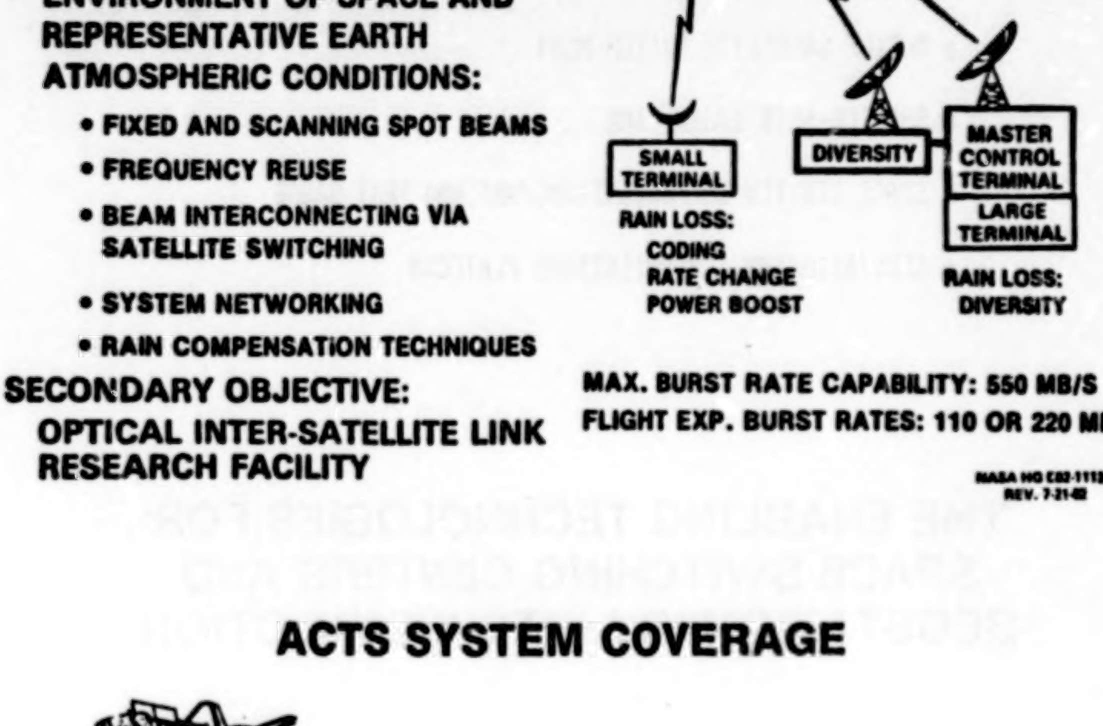
RAIN LOSS:
CODING
RATE CHANGE
POWER BOOST

RAIN LOSS:
DIVERSITY

MAX. BURST RATE CAPABILITY: 550 MB/S
FLIGHT EXP. BURST RATES: 110 OR 220 MB/S

NASA HQ EC82-1112(1)
REV. 7-21-82

ACTS SYSTEM COVERAGE



LASER

STEERABLE ANTENNA

SWITCH

MBA

HOPPING SPOT BEAM ANTENNA

ALASKA

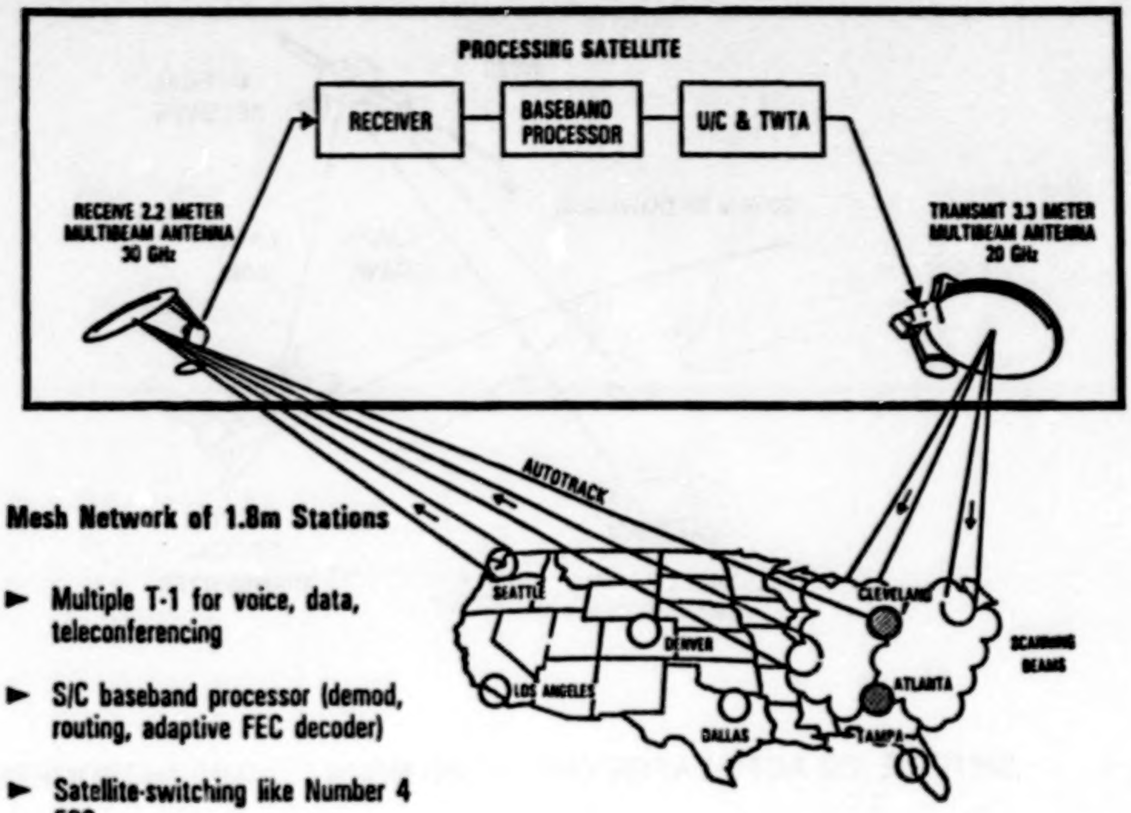
HAWAII

CARIBBEAN

FLEXIBLE COVERAGE

NASA HQ EC86-484 (1)
3-10-86

ACTS 30/20 GHz Experimental System (CPS Mode)

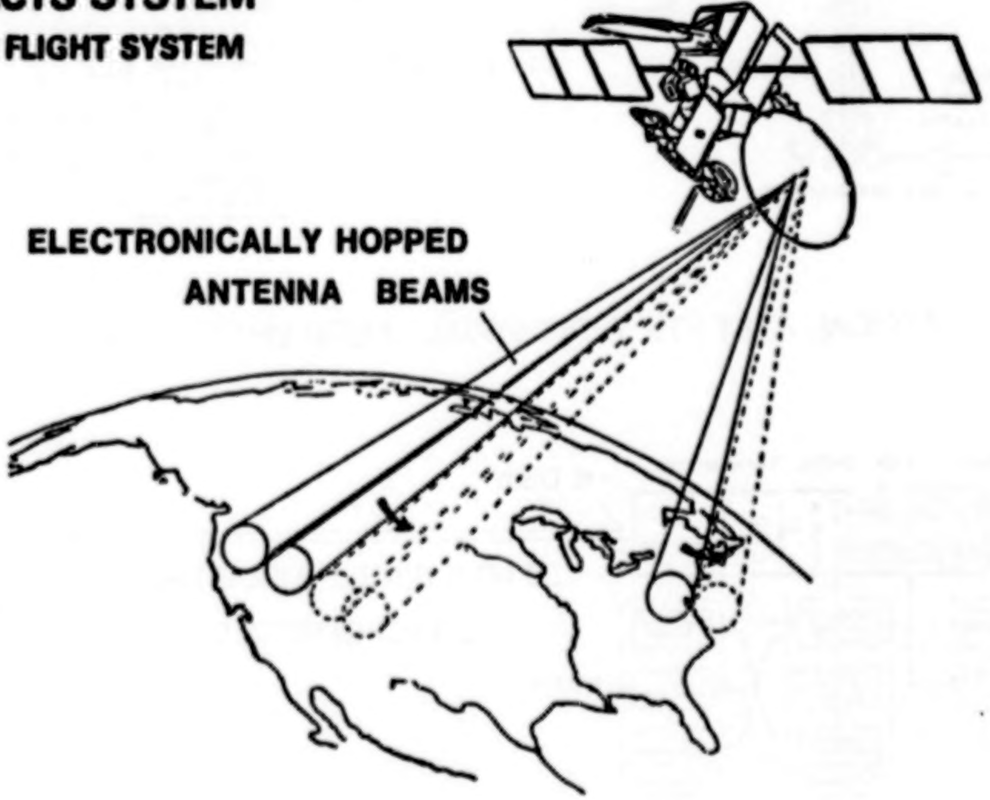


Mesh Network of 1.8m Stations

- Multiple T-1 for voice, data, teleconferencing
- S/C baseband processor (demod, routing, adaptive FEC decoder)
- Satellite-switching like Number 4 ESS

ACTS SYSTEM

- FLIGHT SYSTEM



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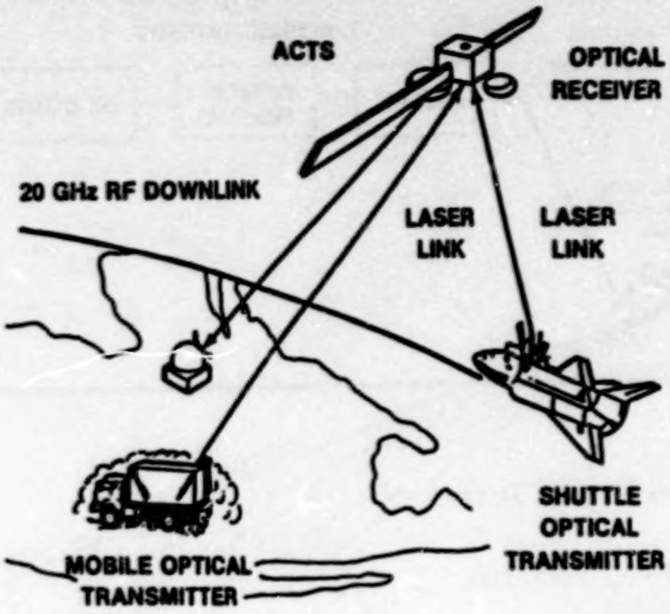
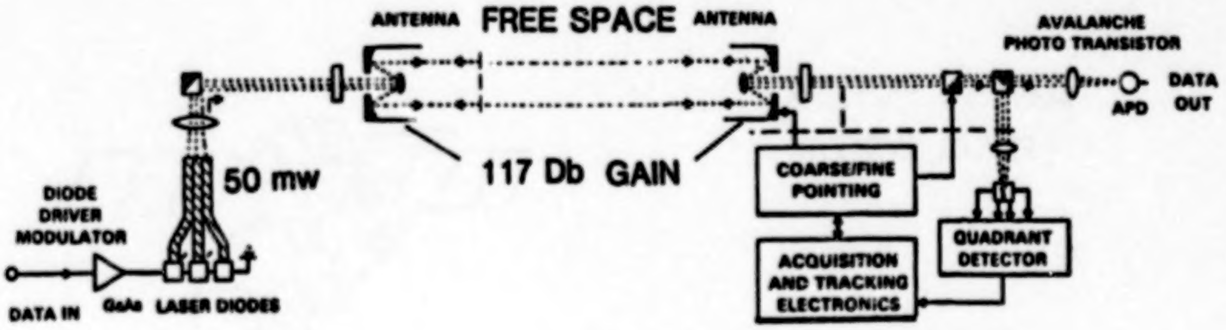
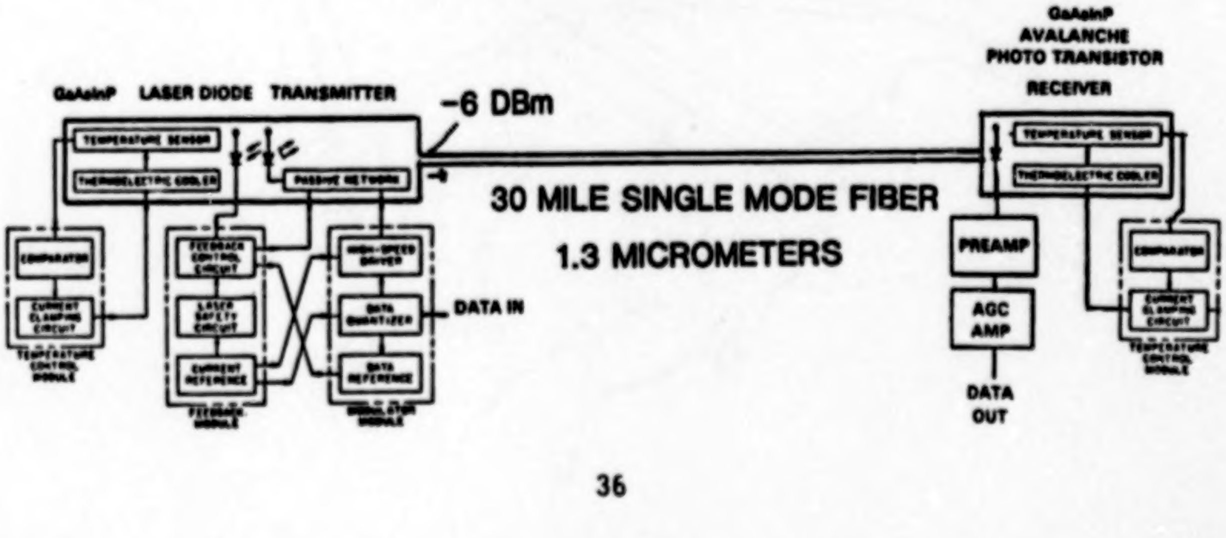
OPTICAL INTER-SATELLITE LINK



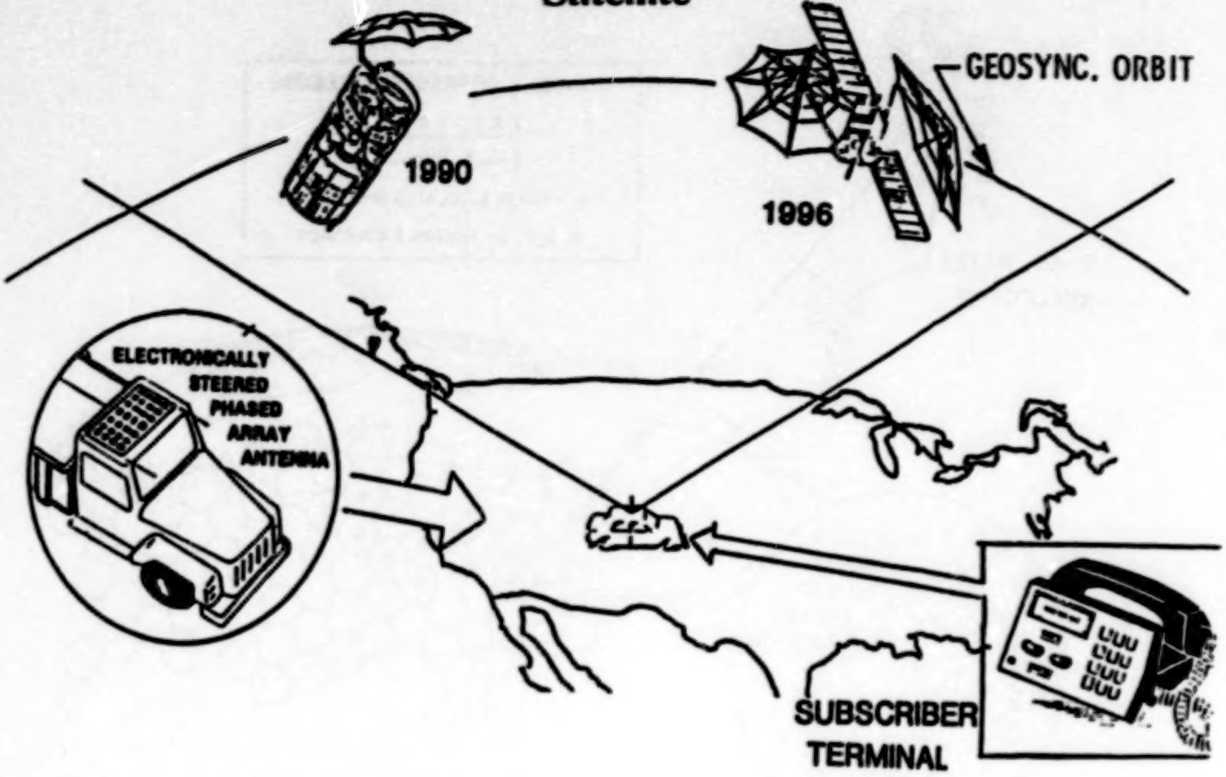
SHUTTLE TO ACTS LASER LINK −220 MBPS 0.86 MICROMETERS



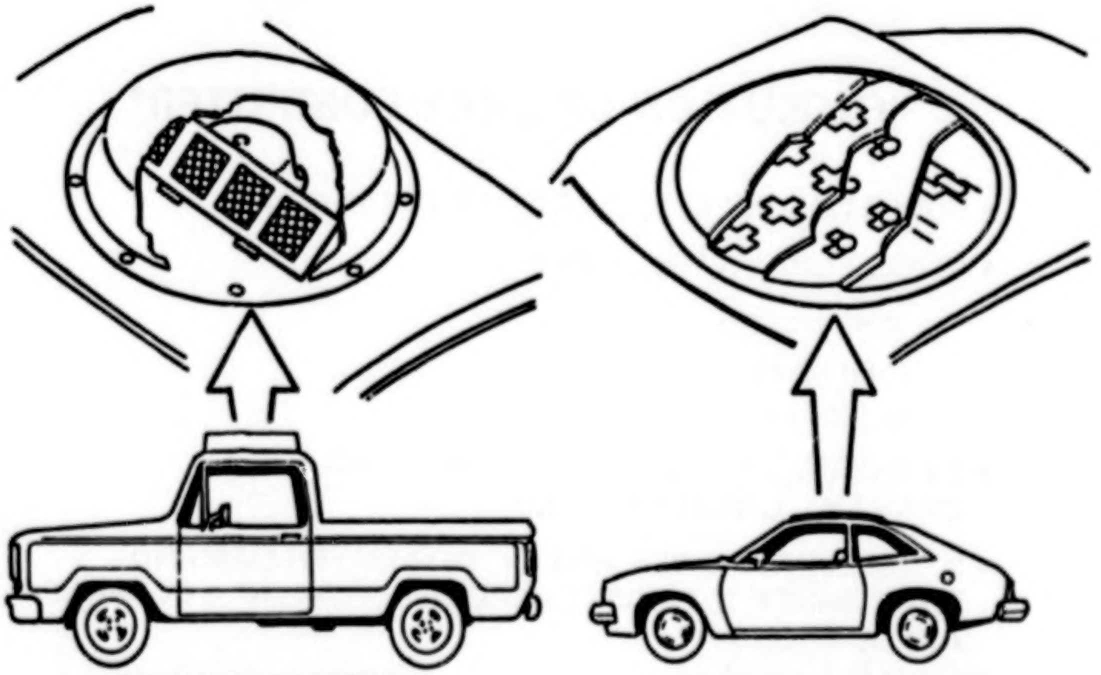
TYPICAL AT&T FTX TERRESTRIAL FIBER OPTIC 430 MBPS LINK



Land Mobile Satellite


GEOSYNC. ORBIT
1990
1996
ELECTRONICALLY STEERED PHASED ARRAY ANTENNA
SUBSCRIBER TERMINAL

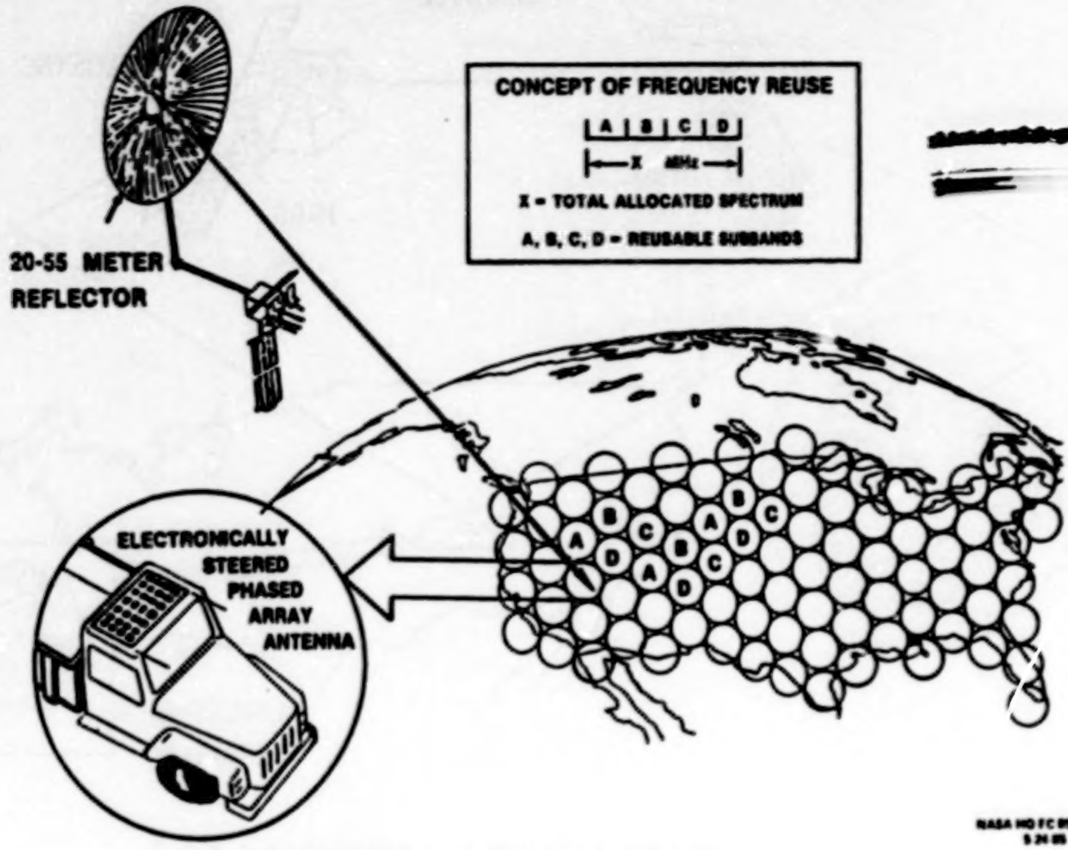
CANDIDATE VEHICLE ANTENNAS FOR MOBILE SATELLITE COMMUNICATIONS



MECHANICALLY STEERED
TILTED MICROSTRIP ARRAY
(7" HEIGHT, 38" DIA.)

ELECTRONICALLY STEERED
PHASED ARRAY
(1.5" HEIGHT, 38" DIA.)

LATER GENERATION SYSTEMS


CONCEPT OF FREQUENCY REUSE
A
B
C
D
X MHz
X = TOTAL ALLOCATED SPECTRUM
A, B, C, D = REUSABLE SUBBANDS
20-55 METER REFLECTOR
ELECTRONICALLY STEERED PHASED ARRAY ANTENNA

[redacted]

NASA HQ FC 85 727(1)
5 24 85

EVOLUTION OF CRAY COMPUTER*

- SUPER COMPUTER GENERATION IS 3 YEARS
- IN 1987 - CRAY 3 WILL HAVE
  - 16 PROCESSORS
  - EACH 1/2 BILLION 64 BIT WORDS
  - 12'' × 8'' × 4''
- BY THE TIME WE GET TO CRAY-6,-- 1995--, CRAY-3 WILL BE HAND HELD
- PROCESSING POWER WILL BE IN GREATER DEMAND THAN BANDWIDTH AS IT BECOMES AVAILABLE IN SPACE APPLICATIONS

*MR. BRETT BERLIN, 1985

EVOLUTION OF TERRESTRIAL SWITCH TECHNOLOGY

TO SIZE AND POWER COMPATIBLE WITH SPACECRAFT

	YEAR					
ITEM	65	71	77	78	81	89
RELATIVE VOLUME	3840	320	80	20	2	1
POWER μWATT/BIT	2800	175	70	20	4	1
SPEED μSEC	5.5	5.5	1.4	.7	.55	.55
MEMORY IN MEGABYTES	1.18	1.18	1.18	.79	1.05	1.0
	SHEET FARRITE	CORE	SEMICON-DUCTOR	SEMICON-DUCTOR	SEMICON-DUCTOR	SEMICON-DUCTOR
	104 FT. LONG		4K RAM	16K RAM	64K RAM	256K RAM

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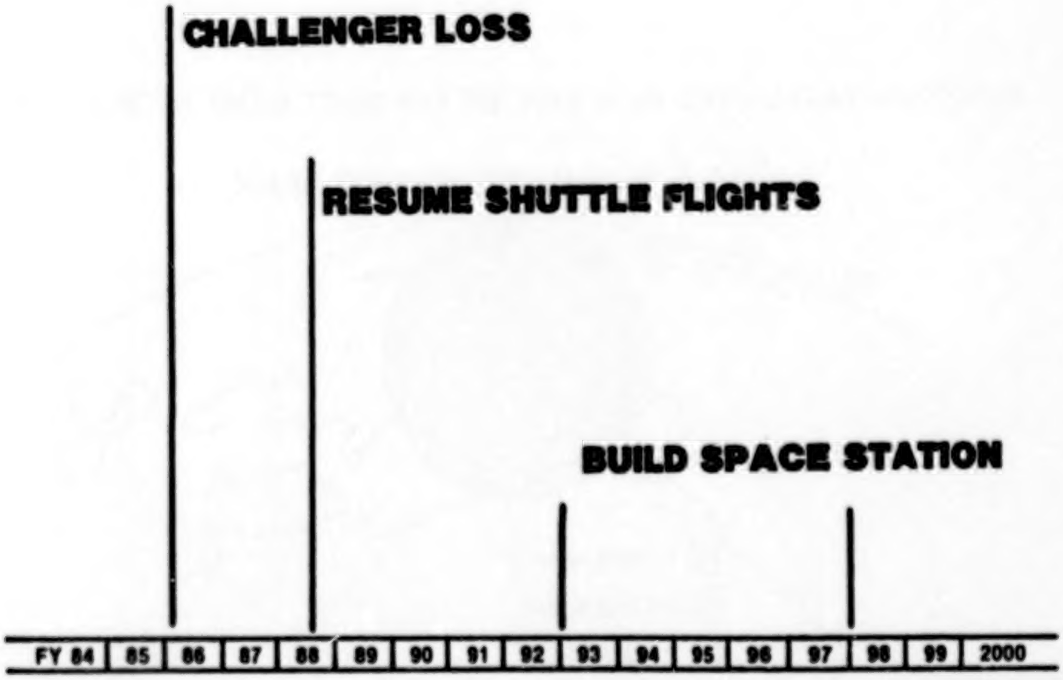
[illegible]

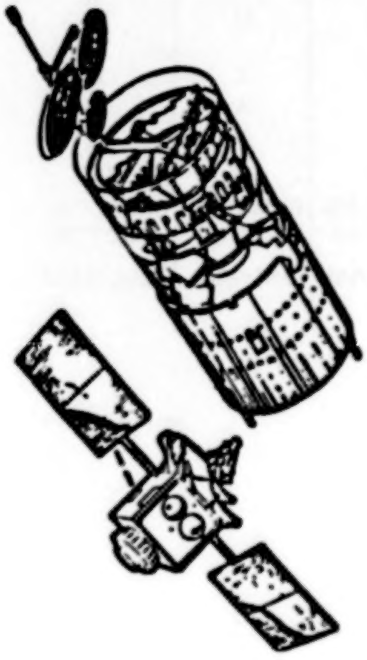
IMPACT OF CHALLENGER DISASTER



THE PATHS OF INTERCONNECTIVITY SPACE–EARTH ANTENNA BEAMS

CONVENTIONAL

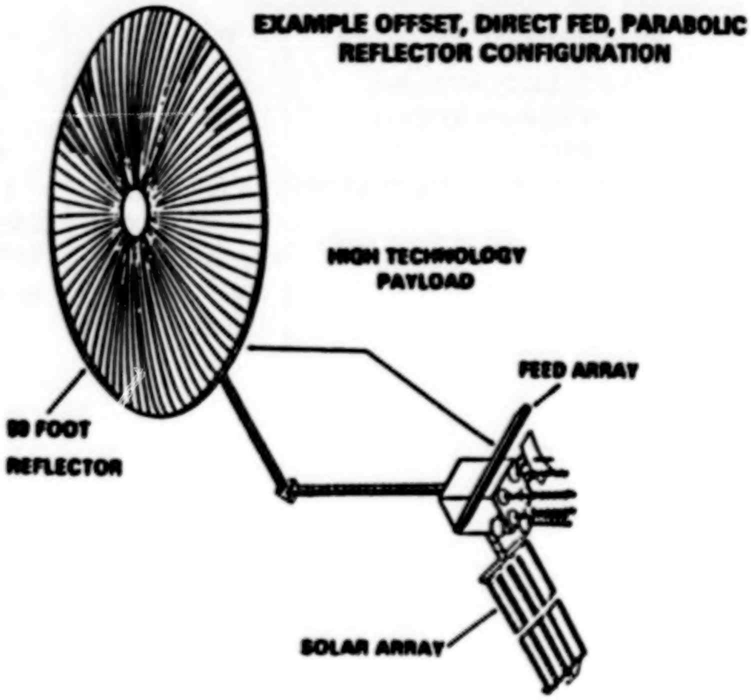
SATELLITE DESIGN



WILL NOW CONTINUE

FUTURE SATELLITE DESIGN USING SPACE STATION

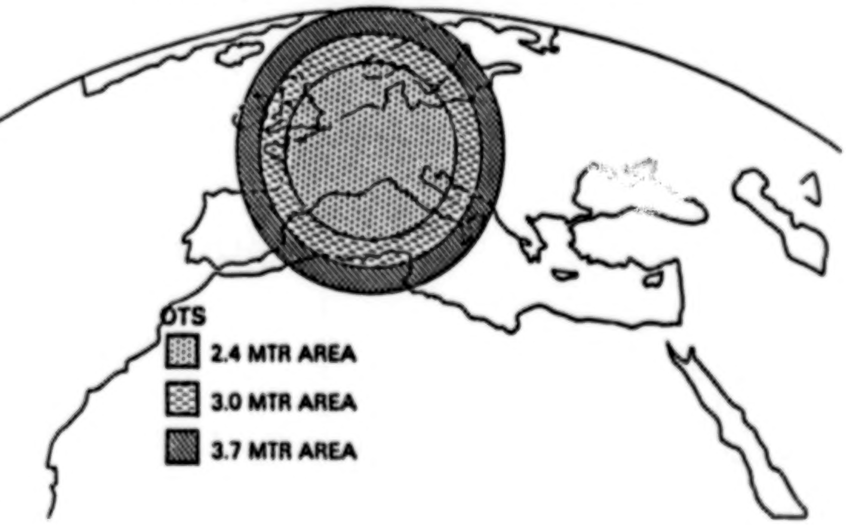
AS ASSEMBLY BASE



WILL BE DELAYED

EUROPEAN SATELLITES WITH CENTER FED SPOT BEAM ANTENNAS – OTS

O.T.S. GROUNDPRINT-SPOT BEAM



Satellite Television's new service is directed throughout Europe by the European Space Agency and the "OTS Satellite"

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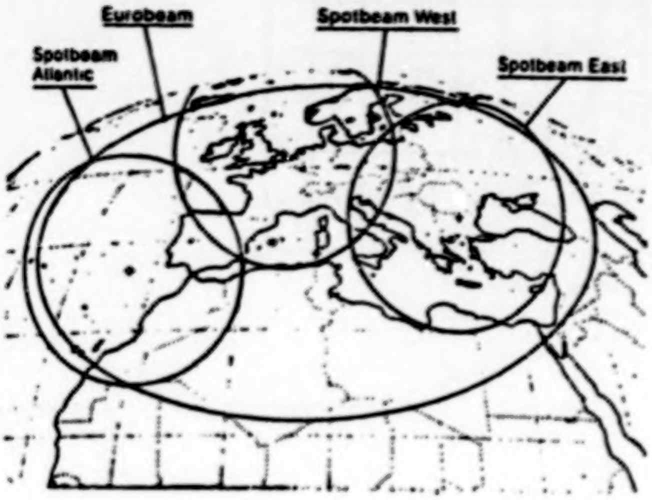
EUROPEAN SATELLITES WITH CENTER FED SPOT BEAM ANTENNAS–ECS

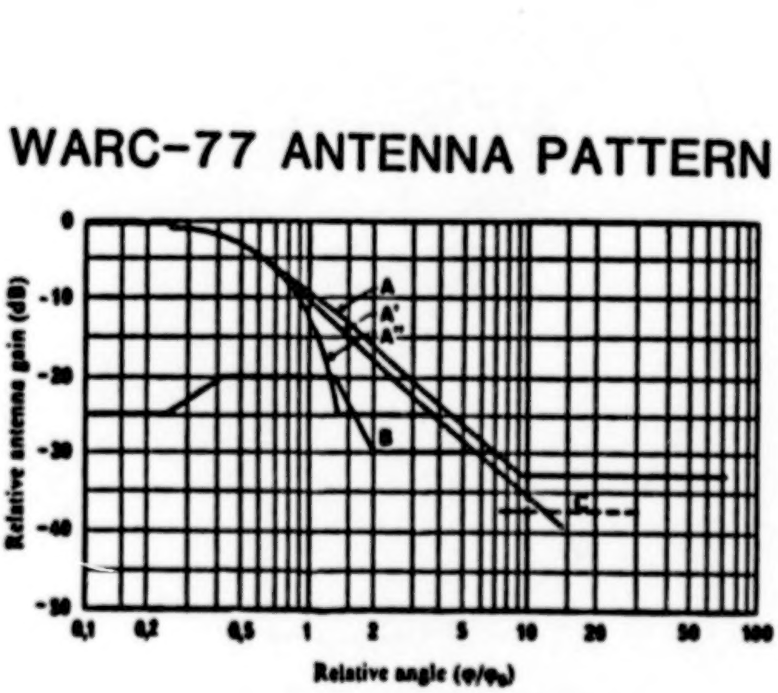


The TV and telecommunications beams of ECS

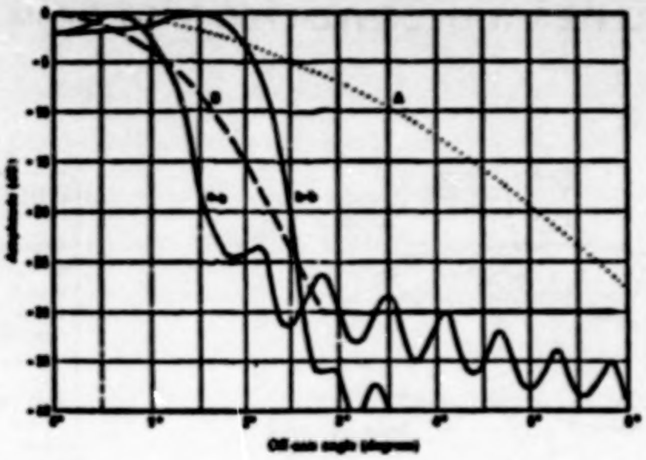
INVESTMENT IN ECS

Country	ECS Share
Austria	1.97
Belgium	4.92
Cyprus	0.97
Denmark	3.28
Finland	2.73
France	16.40
West Germany	10.82
Greece	3.19
Ireland	0.22
Italy	11.48
Luxembourg	0.22
Netherlands	5.47
Norway	2.51
Portugal	3.06
Spain	4.64
Sweden	5.47
Switzerland	4.36
Turkey	0.93
United Kingdom	16.40
Yugoslavia	0.96
	100.00%

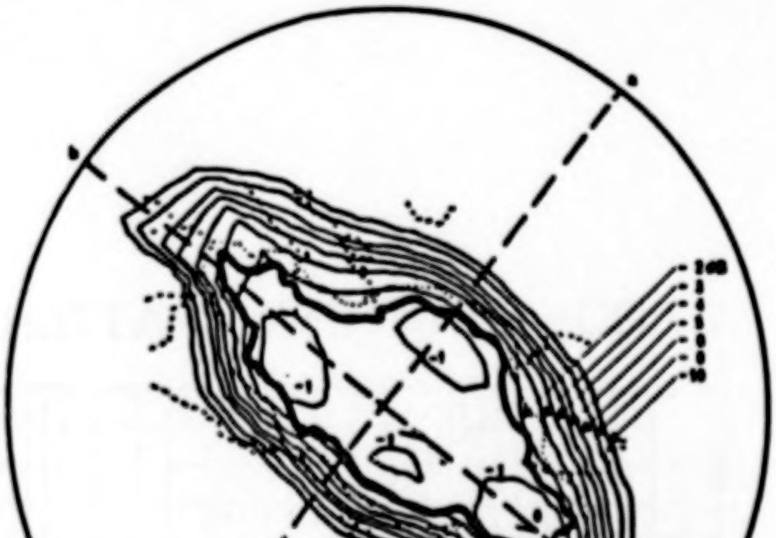
WARC–77 ANTENNA PATTERN



CONTOURED ANTENNA PATTERN



MULTI–BEAM ANTENNA CONTOURING A COUNTRY



Computed shaped beam pattern at 11.379 GHz for a 21-horn offset-fed parabolic reflector system

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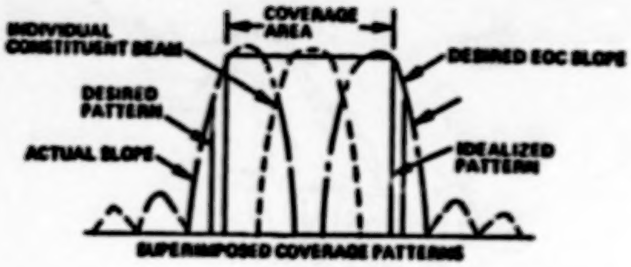
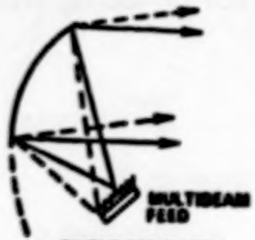
MULTIPLE-FEED OFFSET FED SATELLITE ANTENNA AND SUPERIMPOSED BEAM PATTERNS FOR SHAPED AREA COVERAGE ON EARTH



SUPERIMPOSED COVERAGE PATTERNS



a. SIMPLE OFFSET-FED REFLECTOR

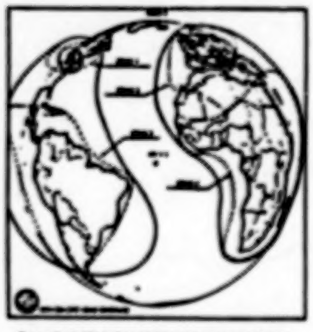
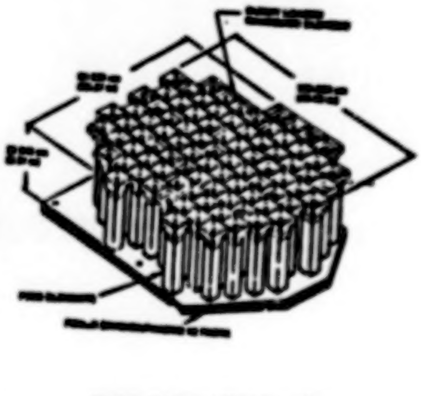


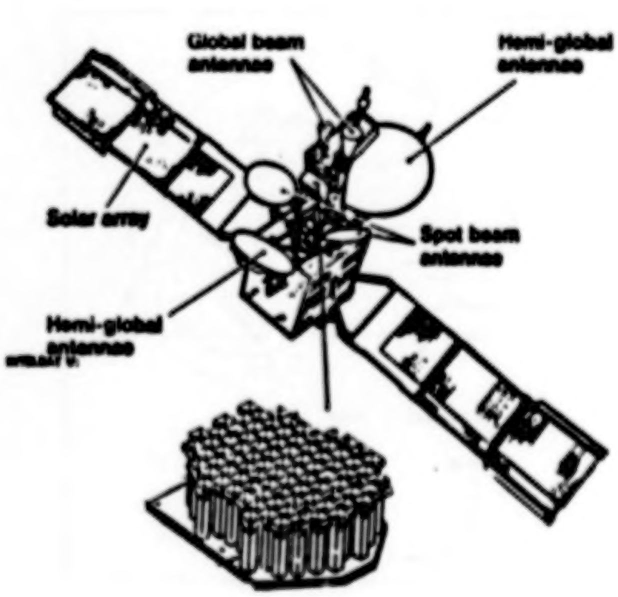
Figure 9. INTELSAT VI COVERAGE CONTOURS FOR THE AOR FROM [illegible] DEGREES EAST LONGITUDE

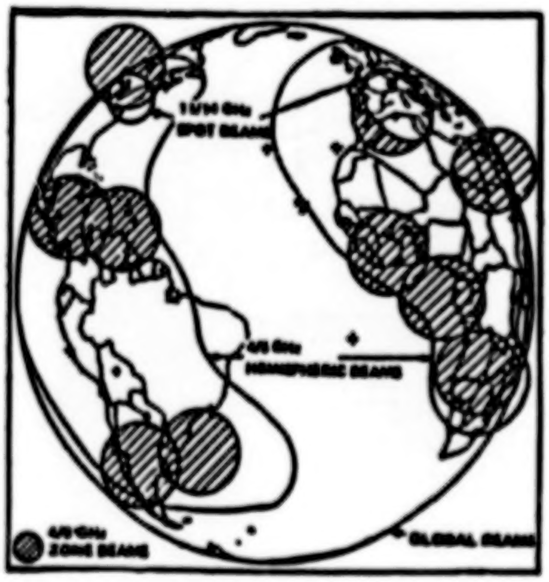
Transmit Feed Array



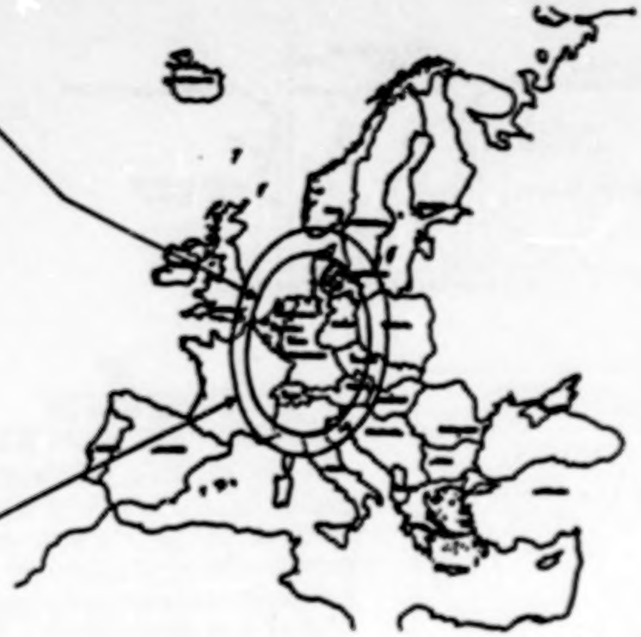
Intelsat V Antenna Feed Assembly

MULTIPLE AREA COVERAGE INTELSATS IV IVA V VA VI





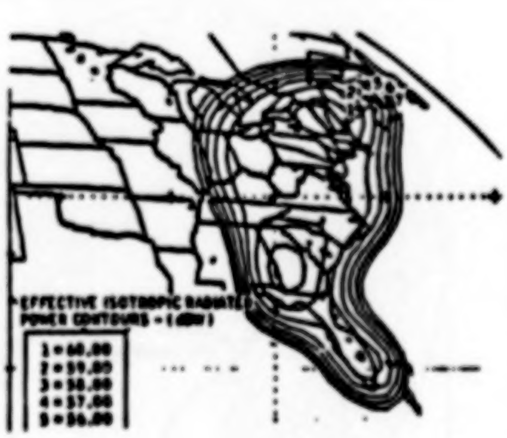
HAZARDS OF APRIORI PLANNING


WARC-77 COVERAGE WITH1977 LNA TECHNOLOGY IN EARTH STATION

1983 LNA TECHNOLOGY

CONTOURED ANTENNA BEAM EXAMPLES

COMSAT STC DBS



ARABSAT

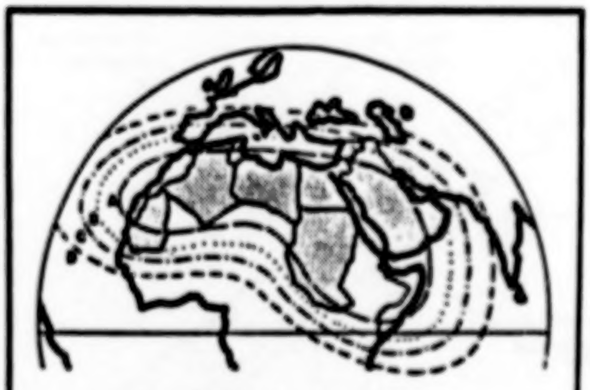


Figure 1: Arabsat Coverage

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SATELLITES WITH CONTOURED BEAM ANTENNAS

RCA SATCOMS

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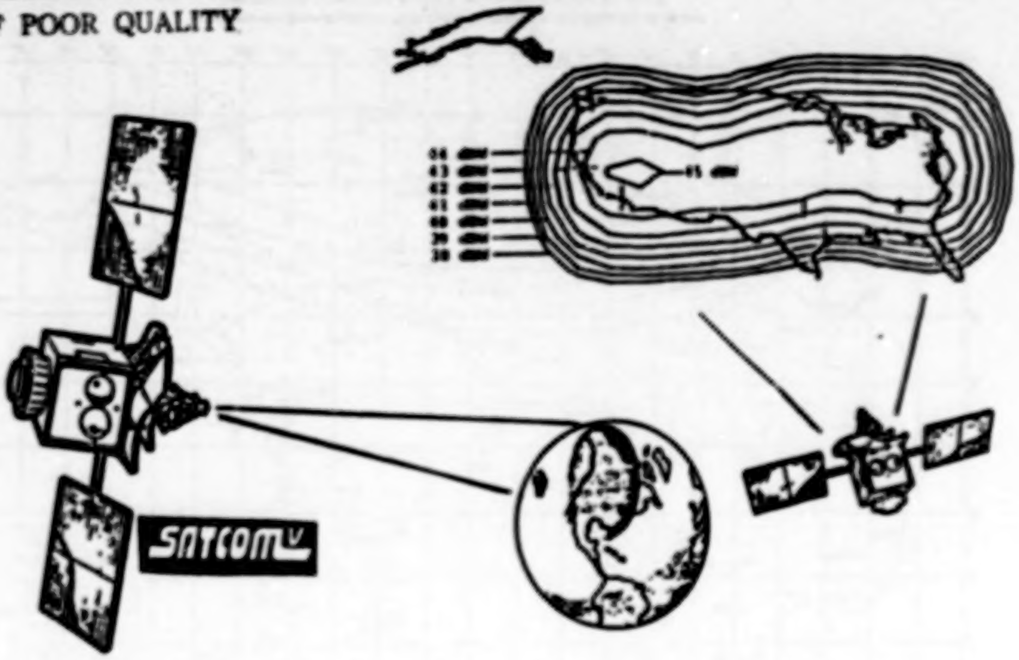
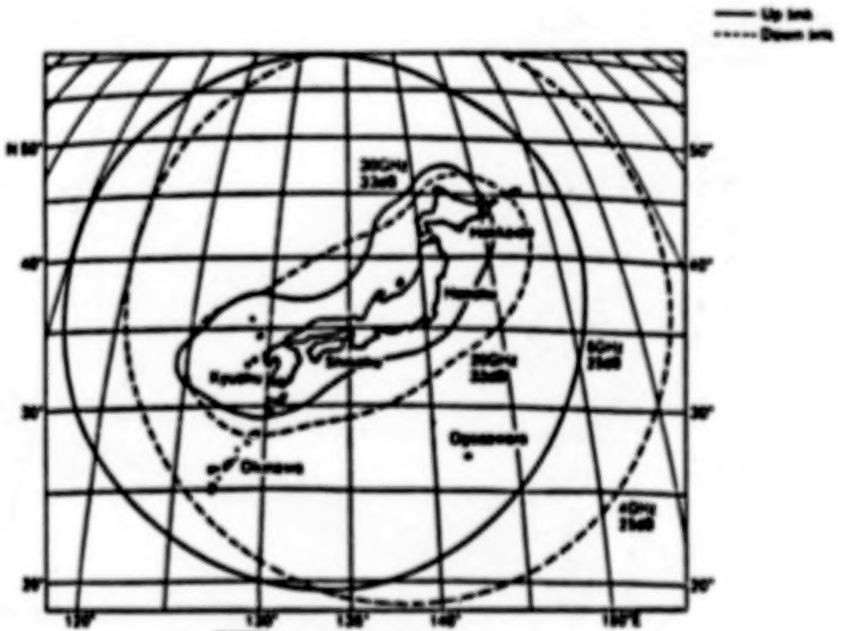


JAPAN CS-2A 30/20 GHZ ANTENNA PATTERN



CS-2 Communications Area

USSR STATSIONAR T2 CONTOURED 716 MHZ BEAM USING 96 HELICAL ANTENNA ARRAY

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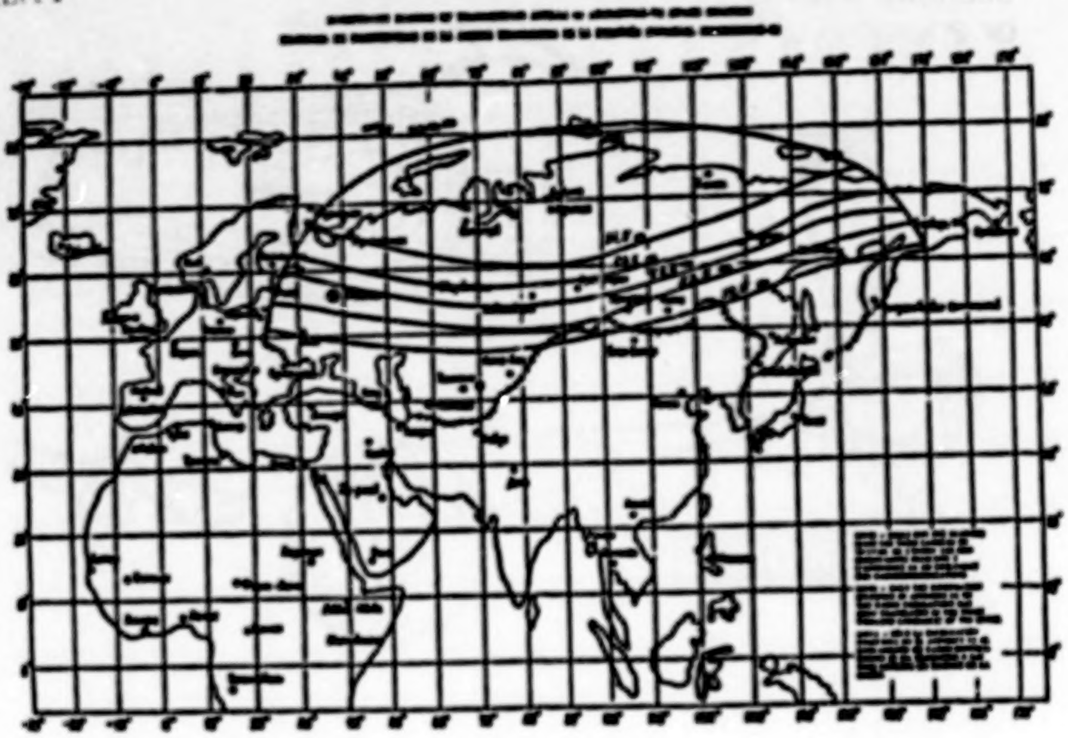
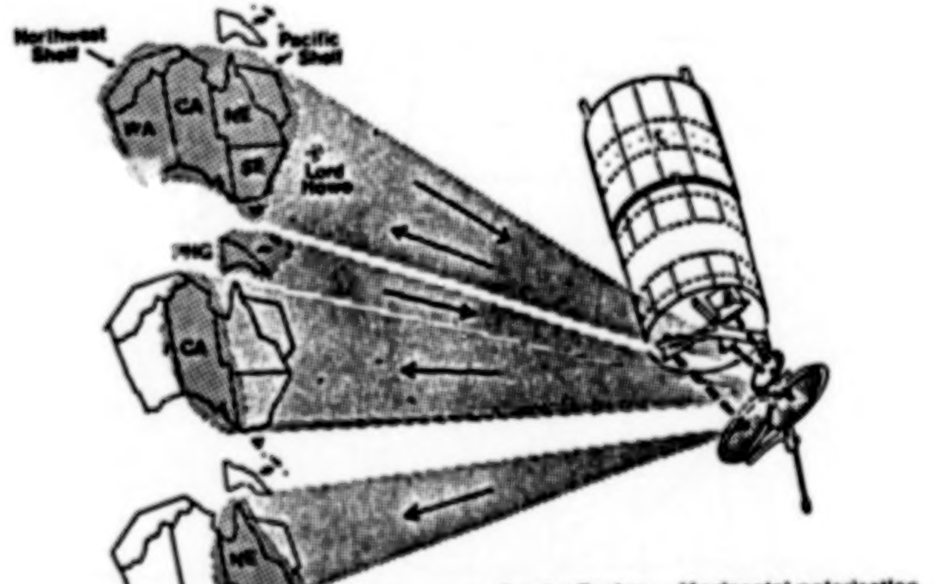
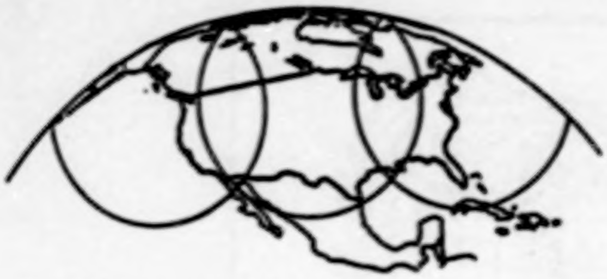


MULTIPLE BEAM AUSSAT

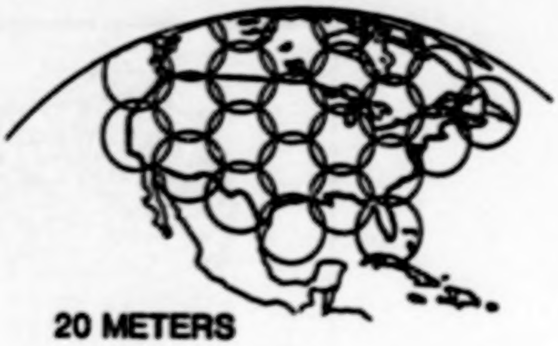


Front reflector — Horizontal polarisation

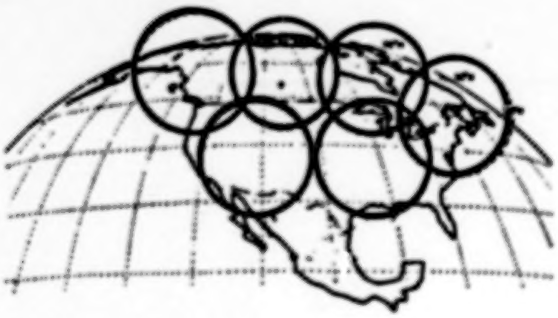
IMPACT OF ANTENNA SIZE ON U S COVERAGE AT 860 MHZ



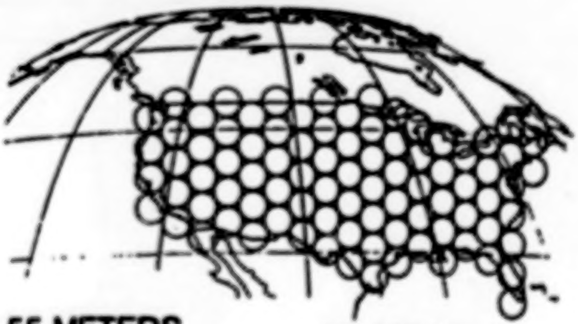
5.5 METERS



20 METERS

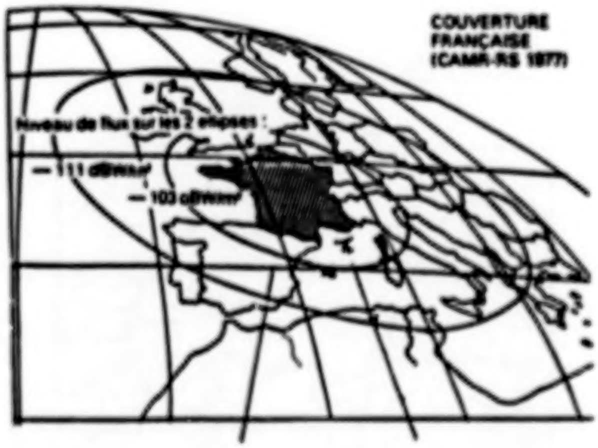


9 METERS



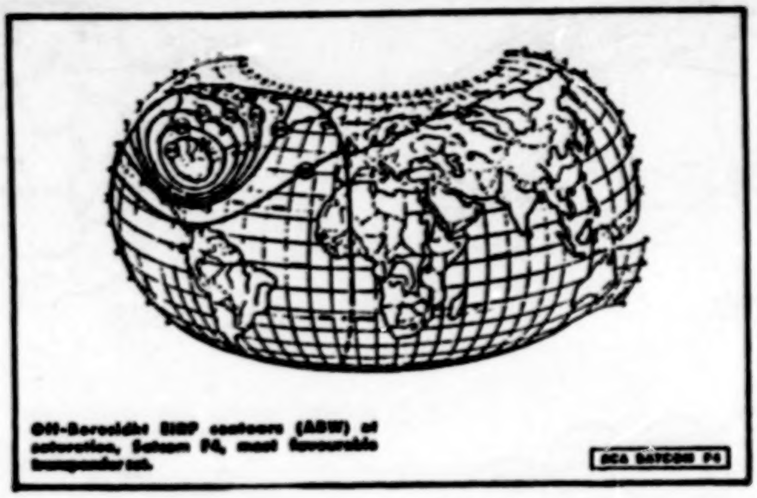
55 METERS 87 CELLS

THE POLITICS OF ANTENNA COVERAGE AND SPILLOVER

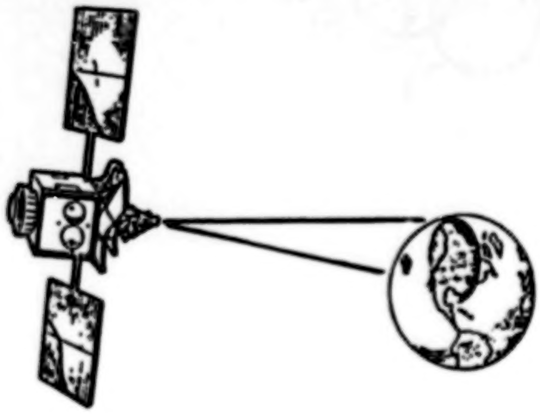

COUVERTURE FRANÇAISE (CAMR-RS 1977)
Niveau de flux sur les 2 ellipses :
— 111 dBW/m²
— 103 dBW/m²

PRIMARY COVERAGE AREA ADJACENT COUNTRY SPILLOVER

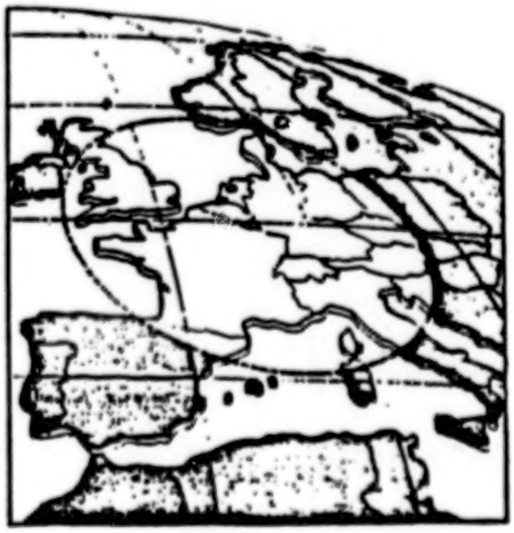
SATCOM F4 SPILLOVER TO EUROPE



Off-Boresight EIRP contours (dBW) at saturation, Satcom F4, most favourable transponder set.



FRENCH TELCOM 1 SPILLOVER TO WARSAW PACT NATIONS



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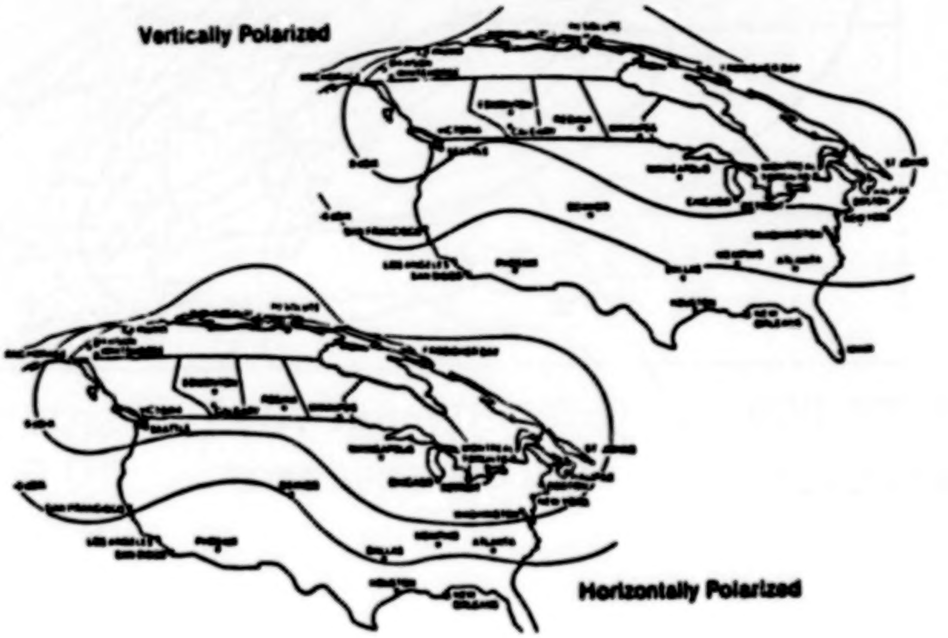
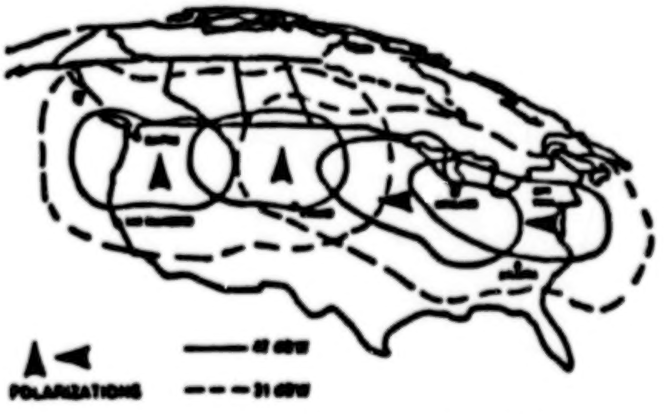
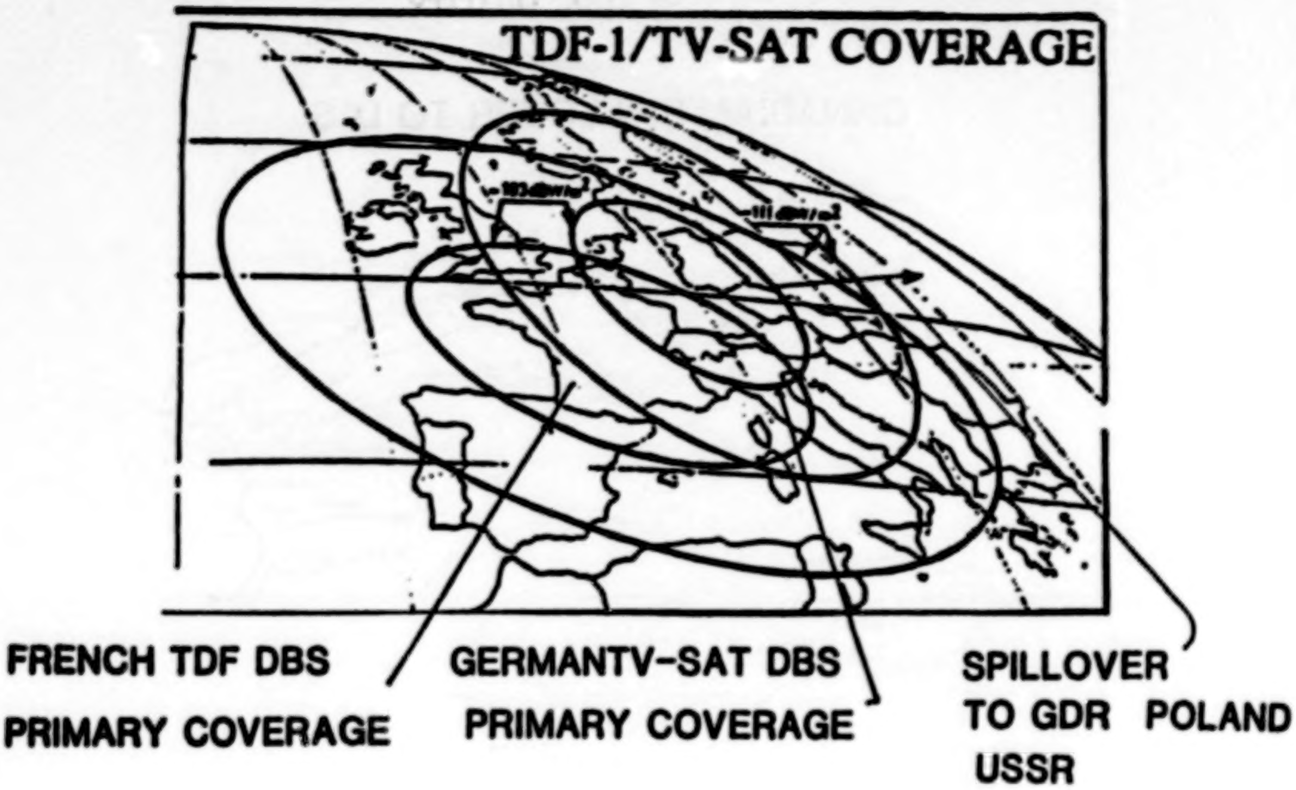
CANADIAN SPILLOVER TO U S



Anik D 6 GHz Receive Pattern (G/T) (Typical)

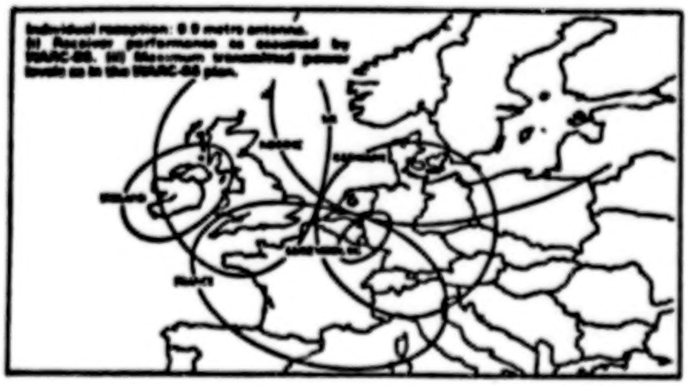


ANIK C3 12GHz TRANSMIT PATTERN (EIRP)
(TYPICAL)



WARC-77 DBS SPILLOVER

IN EUROPE



FRENCH "SPILLOVER"

TO CENTRAL AFRICA

ATHOS 6/4 GHz coverage zones

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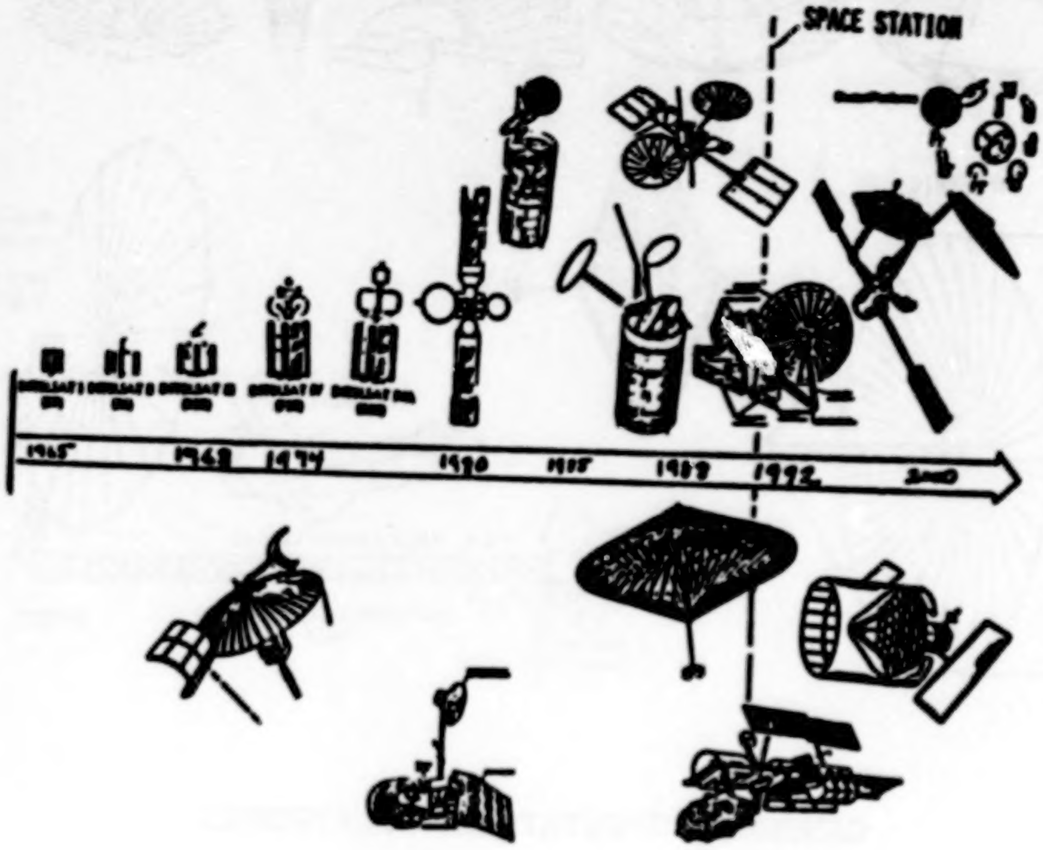
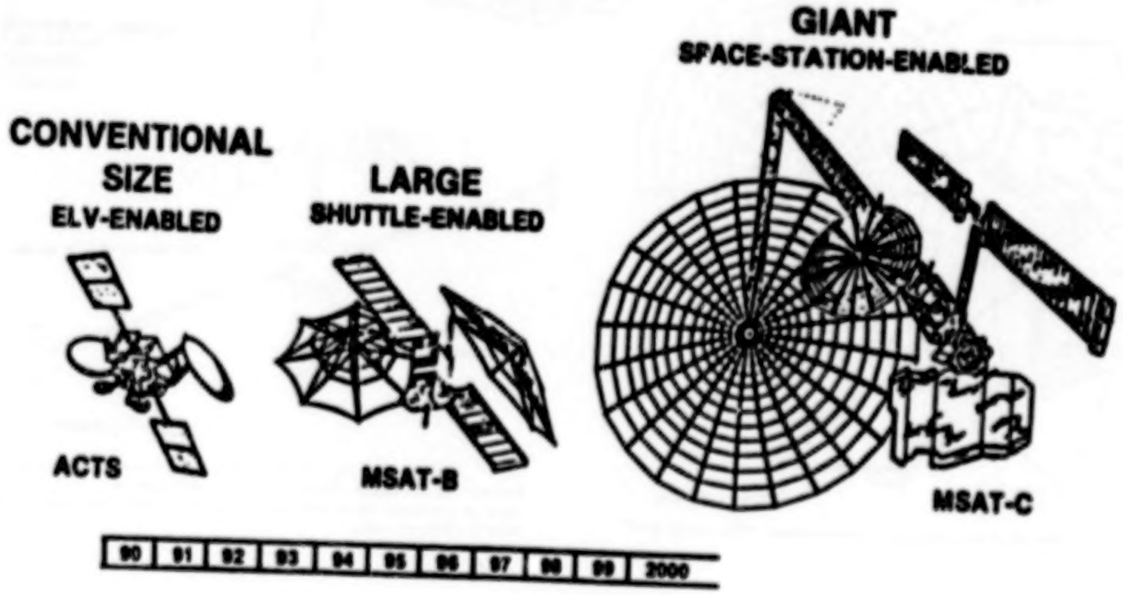
TRANSITION TO GIANT ANTENNAS IN THE SPACE STATION ERA

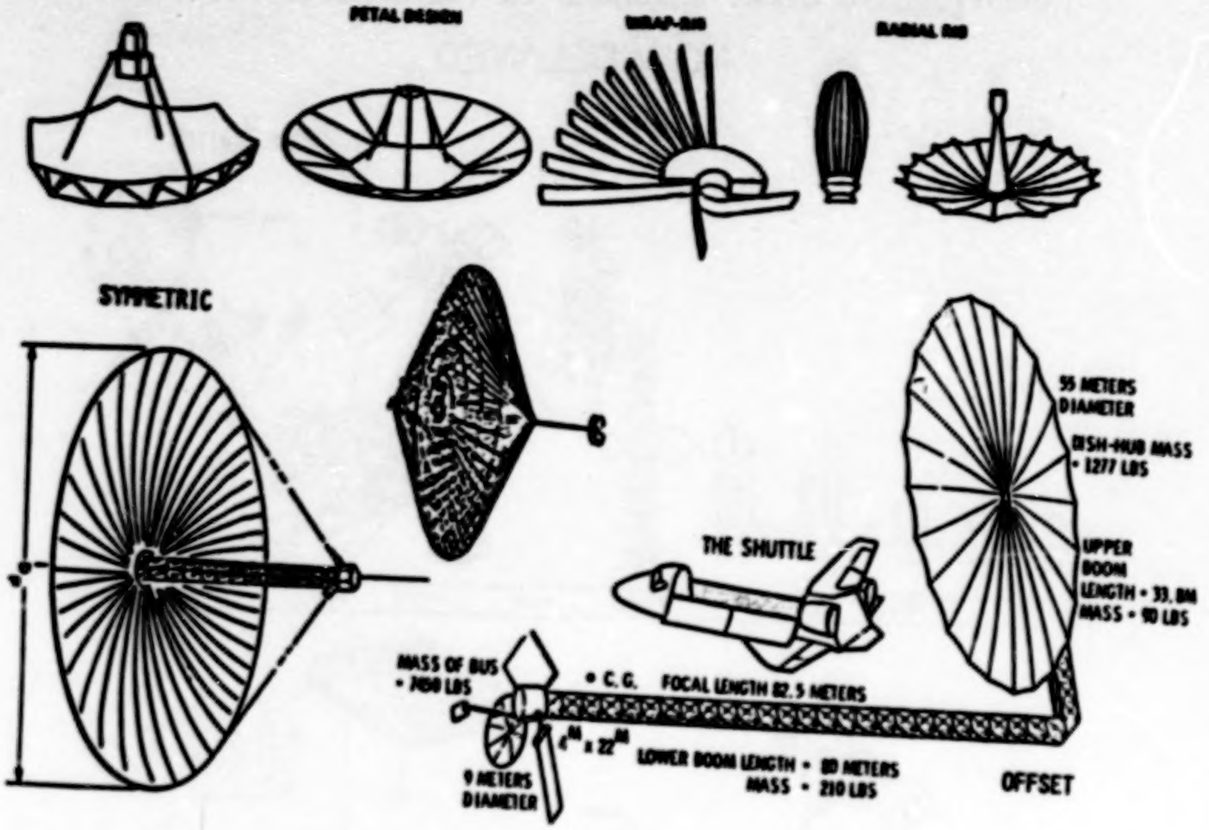
NOW DELAYED



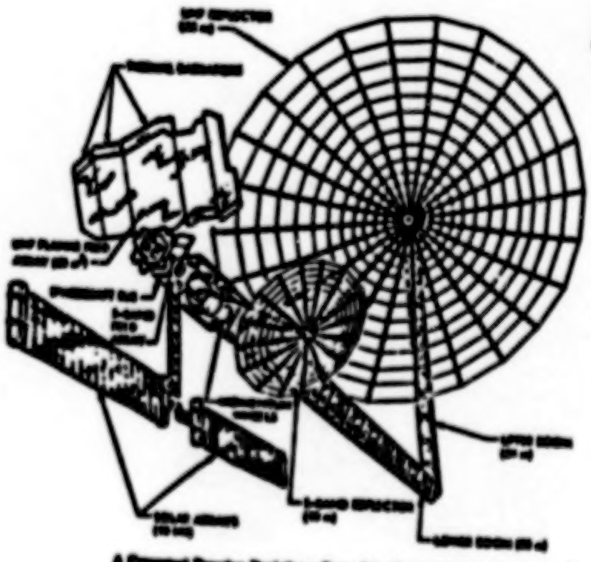
GROWTH IN ANTENNA SIZE



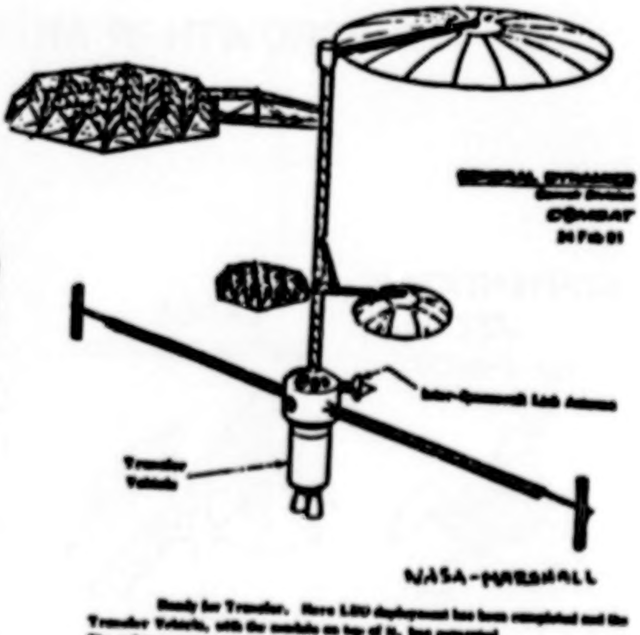
TYPES OF GIANT ANTENNAS FOR UNFURLING



CANDIDATE GEOSTATIONARY PLATFORMS



A Conceptual Drawing Depicting a Twenty-first-Century Mobile Satellite (JPL)

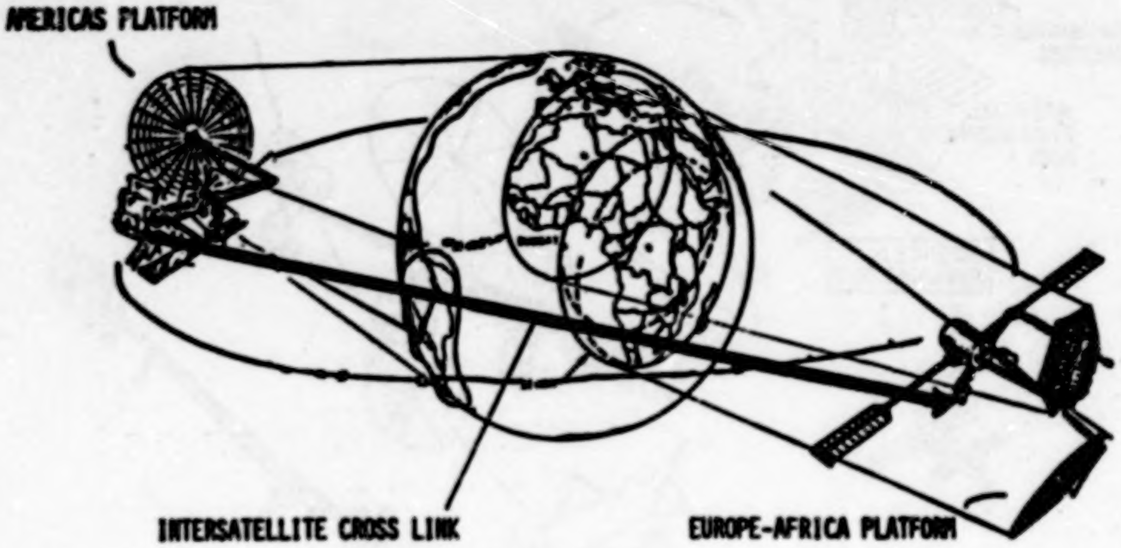


Ready for Transfer. Here LEO deployment has been completed and the Transfer Vehicle, with the module on top of it, has separated. The solar arrays are still in their containers. It may be possible to partially deploy the arrays before transfer.

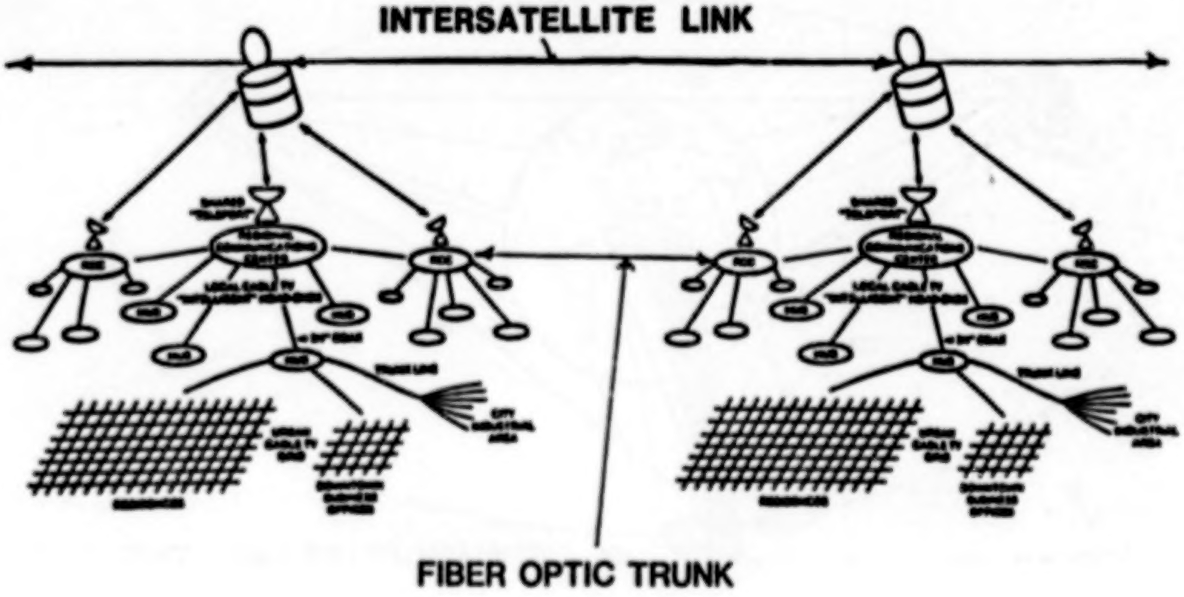
PERSPECTIVE OF THE 2000's

INTERCONNECTIVITY OF REGIONAL PLATFORMS BY INTERSATELLITE LINKS

PERSPECTIVE OF THE 1990'S- INTERCONNECTIVITY OF REGIONAL PLATFORMS BY INTERSATELLITE LINKS

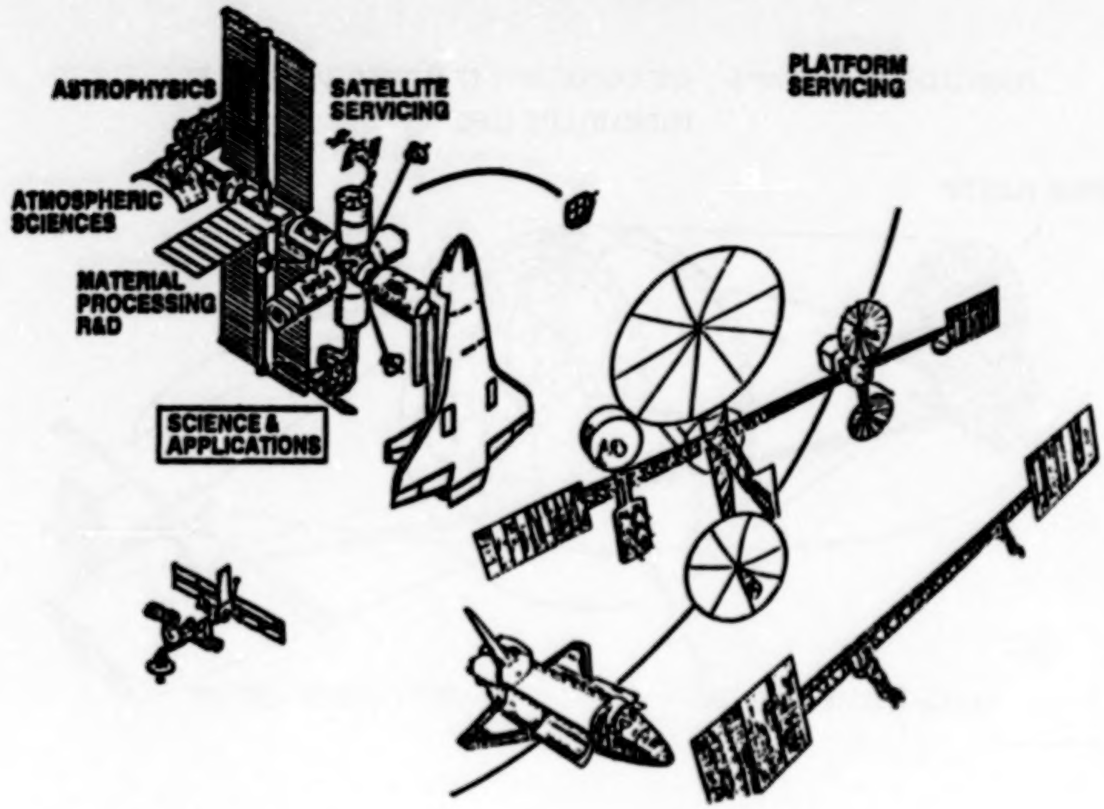


SPACE TERRESTRIAL COMMUNICATION SYSTEM 1990'S

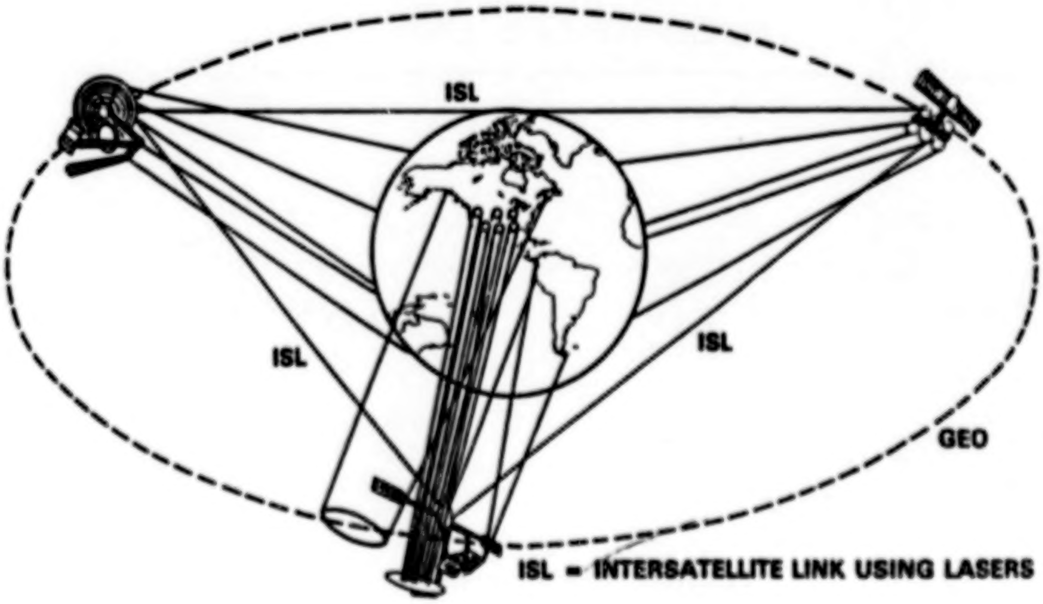


SPACE STATION COMMUNICATIONS

OS SA TECHNOLOGY EC

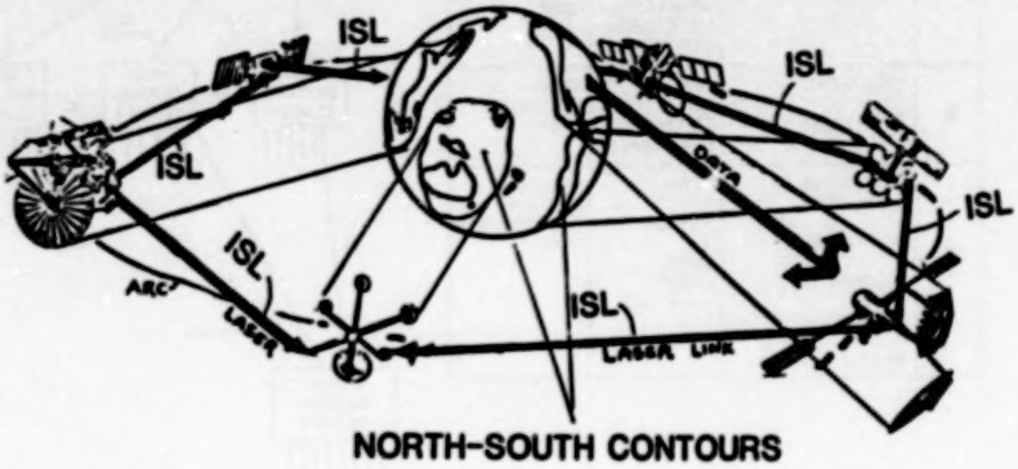


NORTH SOUTH REGIONAL SATELLITE NETWORK FOR GLOBAL INTERCONNECTIVITY

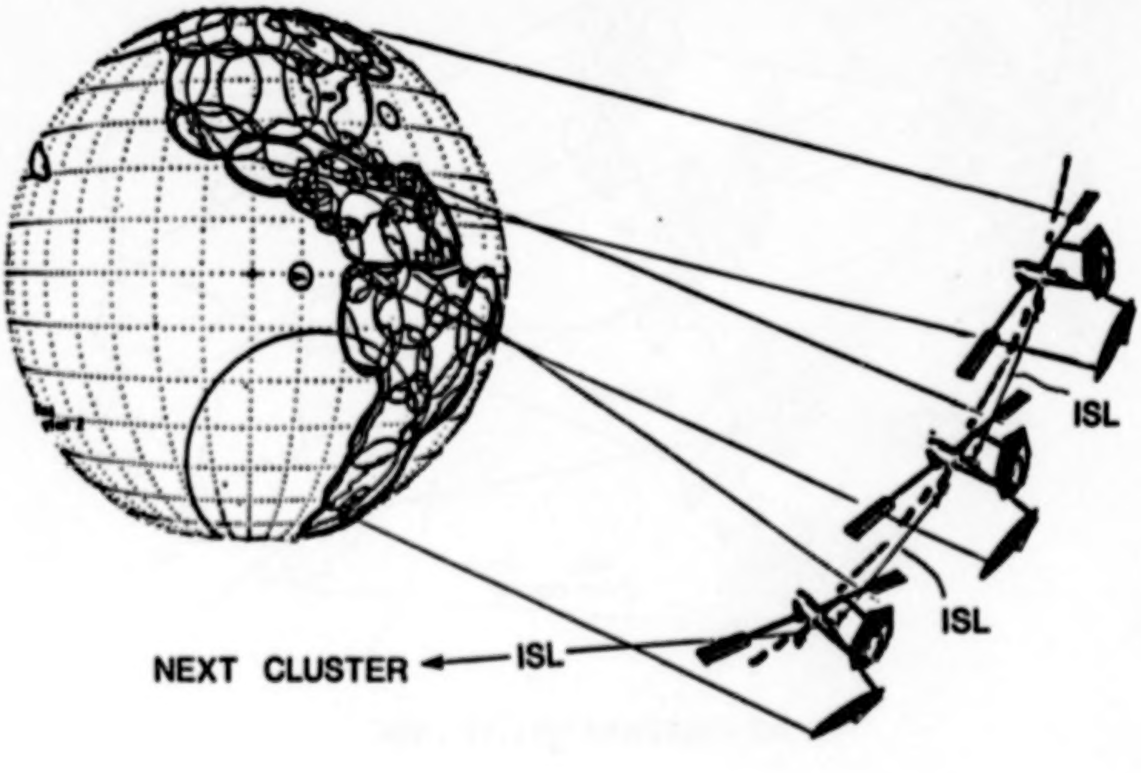


GLOBAL INTERCONNECTIVITY IN THE EARLY 21ST CENTURY

GLOBAL INTERSATELLITE (ISL)
COMMUNICATION SYSTEM 1990's

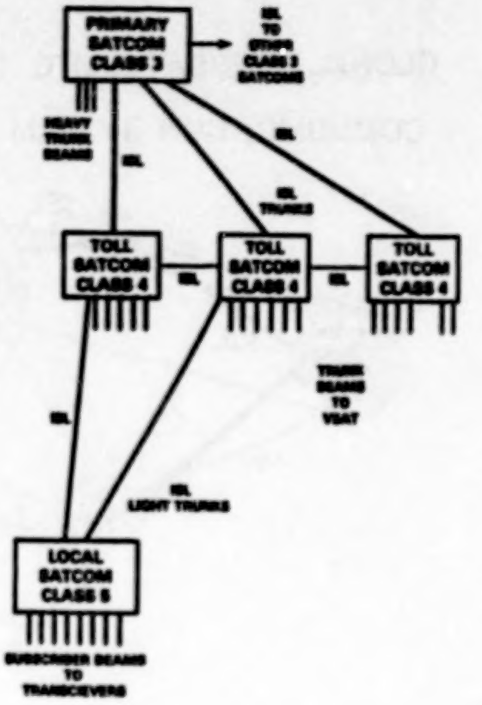


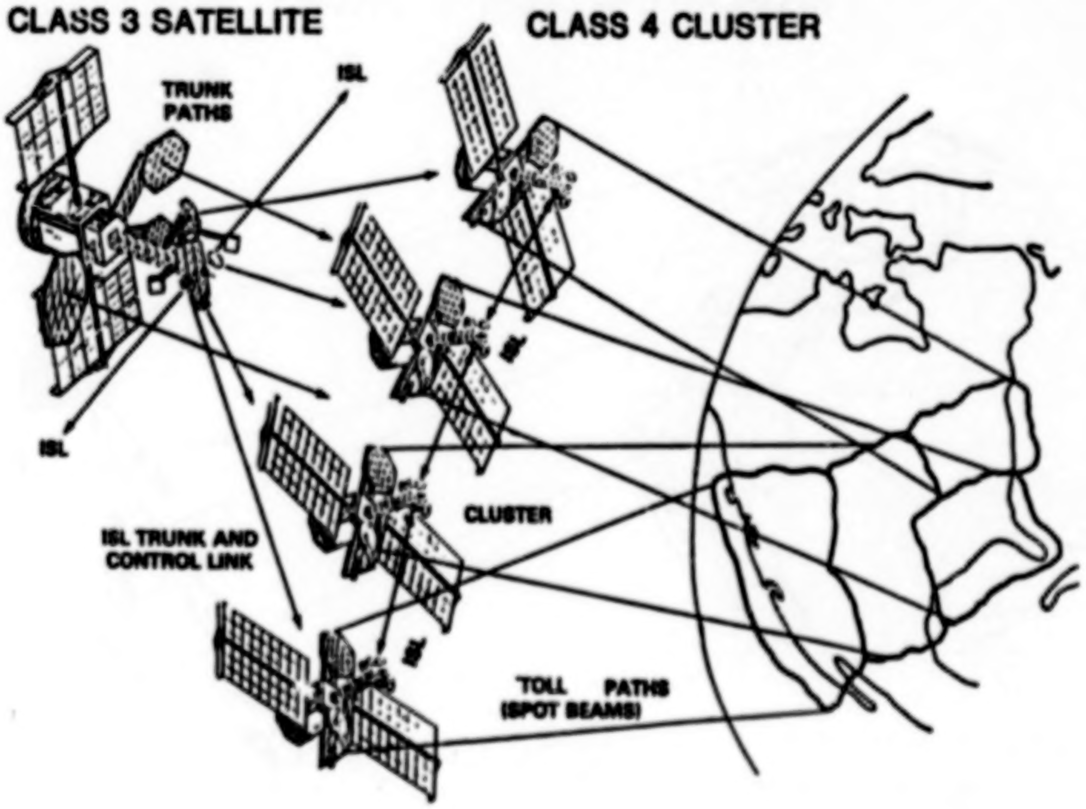
GEOPLATFORM CLUSTER 2000's



SATELLITE EQUIVALENT DIGITAL SWITCH HIERARCHY

CLASS	USERS	SIGNAL TYPE	EARTH STATION
3	HEAVY TRUNK INTERCONNECTS WITH CLASS 4 SATELLITES OR WITH CLASS 3/4 STATIONS ON GROUND	T3 (45 Mbps) — 565 Mbps — 1.6 Gbps (COMPATIBLE WITH EARTH FIBER TRUNK NETWORKS	EXPENSIVE 13 METER HEAVY ROUTE STATIONS <$1M
4	PBX-TO-PBX OR EQUIVALENT	56 Kbps TO T1 (1.54 Mbps) T2 (6.2 Mbps)	VSAT TERMINALS <$10K
5	SUBSCRIBER TO SUBSCRIBER — MOBILE USERS — PC-TO-PC — WRIST-RADIO — PAGING	75 bps TO 9.6 Kbps — VOICE: — 800 — 2.4 Kbps	VERY LOW COST EARTH TRANSCEIVERS <$1K





ISL = INTERSATELLITE LINK

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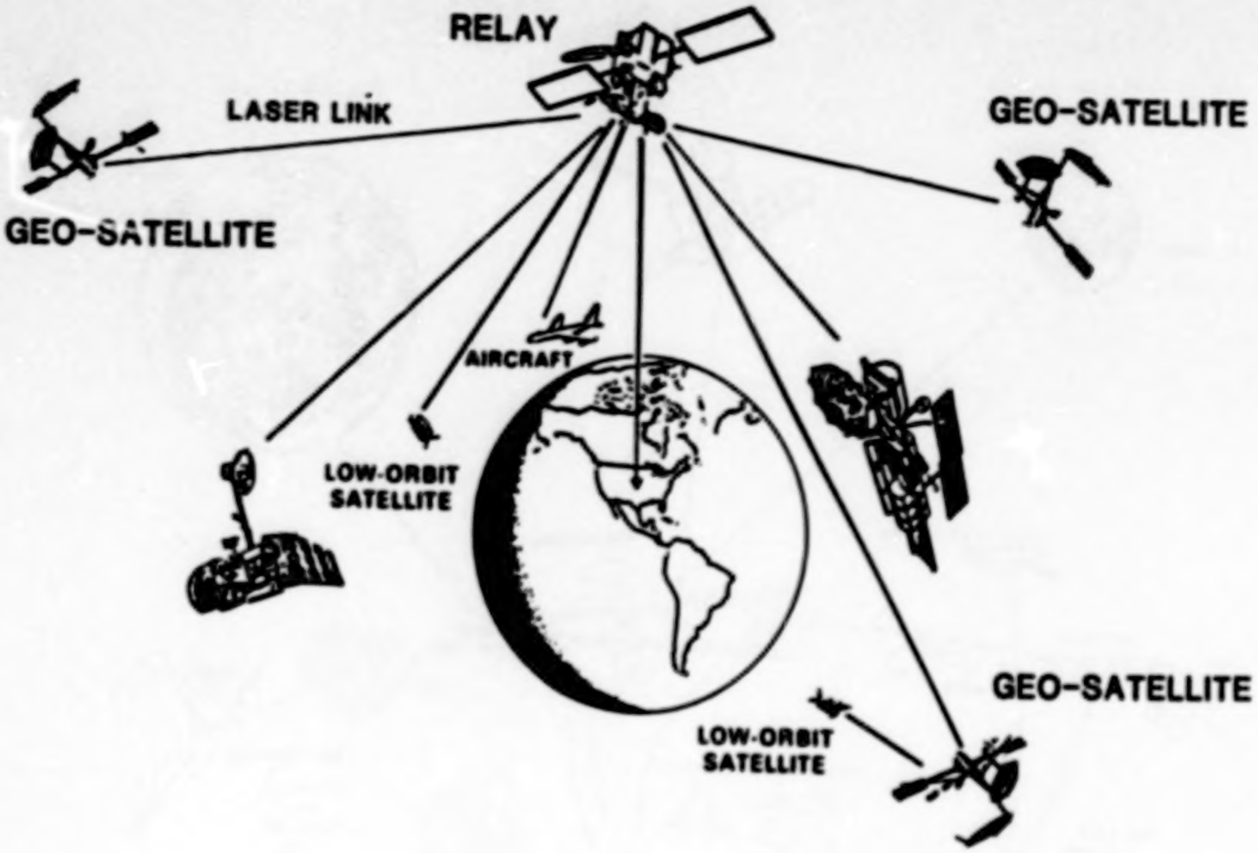
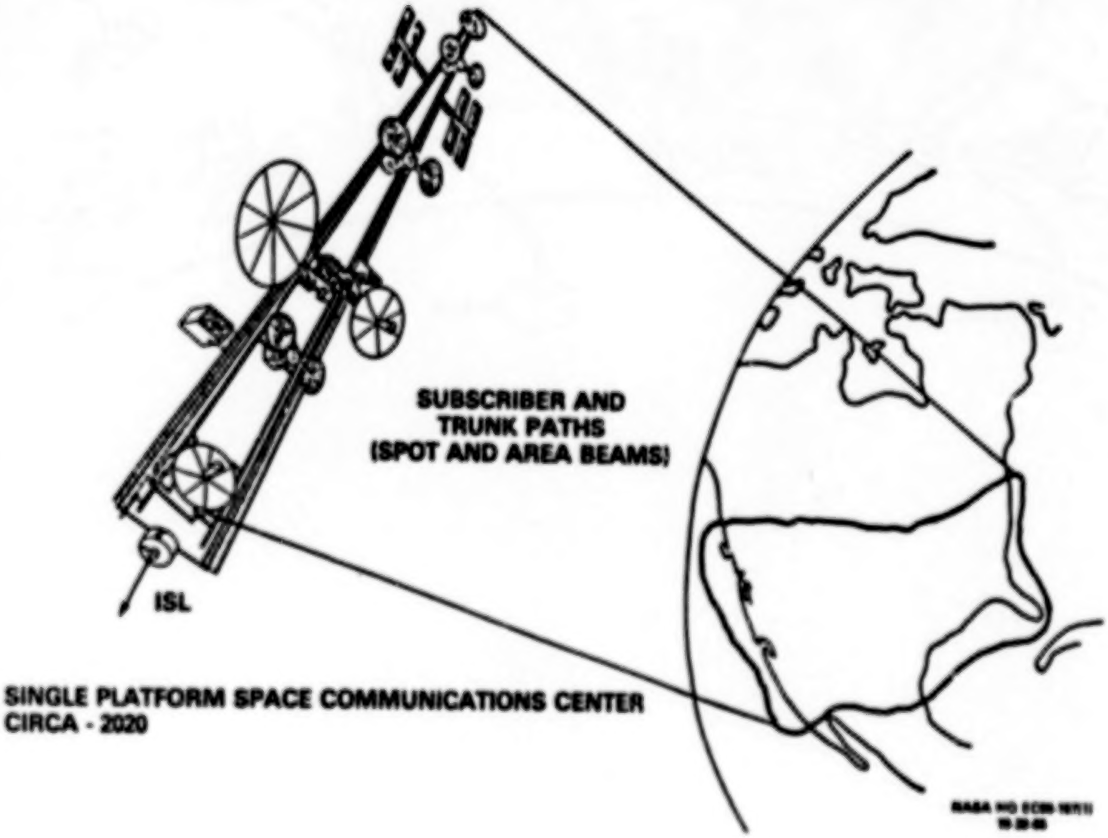
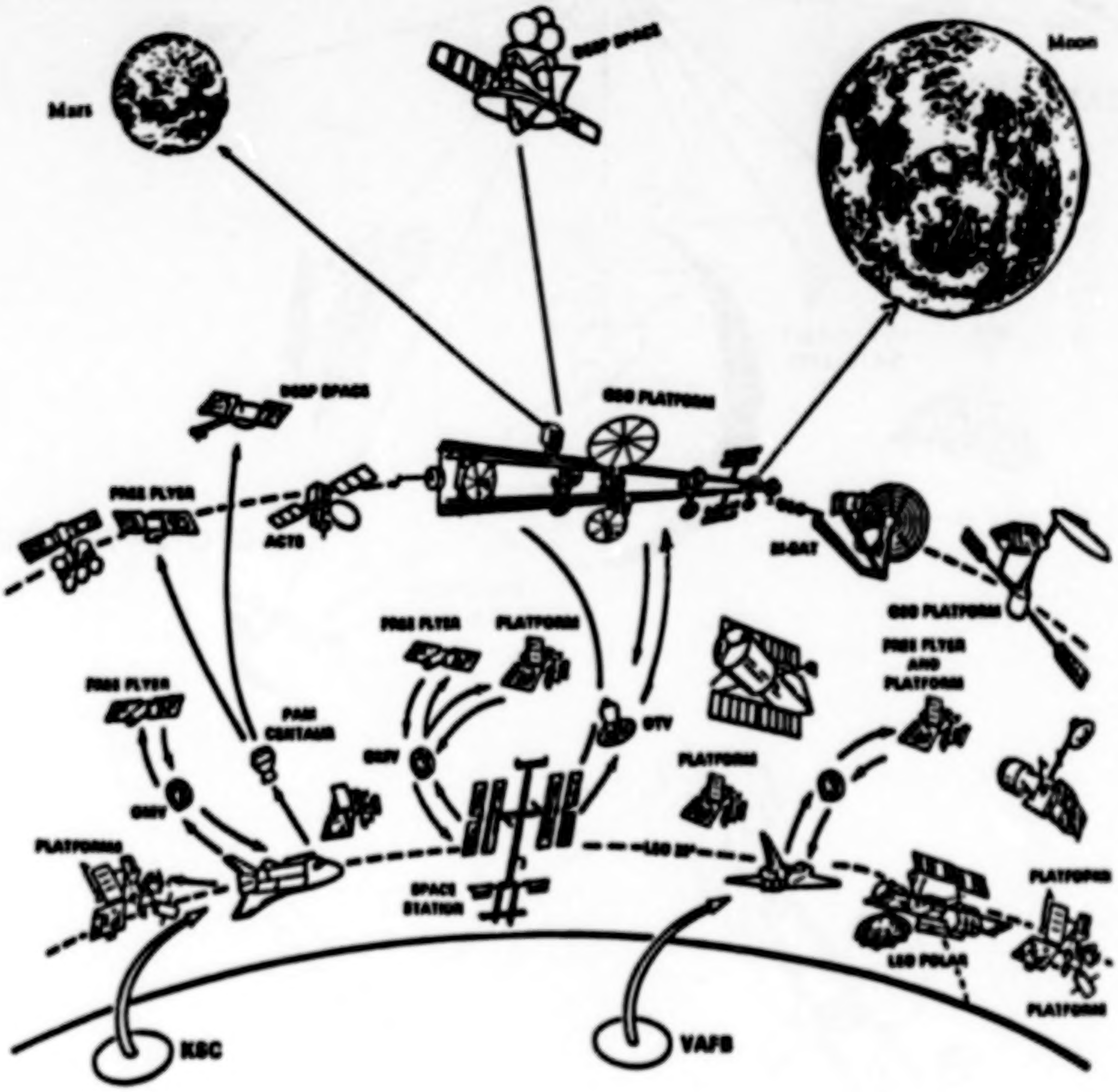
OPTICAL FREQUENCY COMMERCIAL GEOSTATIONARY RELAY SATELLITE




SUBSCRIBER AND TRUNK PATHS (SPOT AND AREA BEAMS)
ISL

SINGLE PLATFORM SPACE COMMUNICATIONS CENTER
CIRCA - 2020

NASA HQ [illegible]



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SPACE ASSEMBLY, MAINTENANCE, AND SERVICING STUDY (SAMSS)

Joseph Wong
U.S. Air Force

AGENDA

- BACKGROUND
- SAMS CONCEPT
- SAMS STUDY
- RELATED STUDIES
- SUMMARY

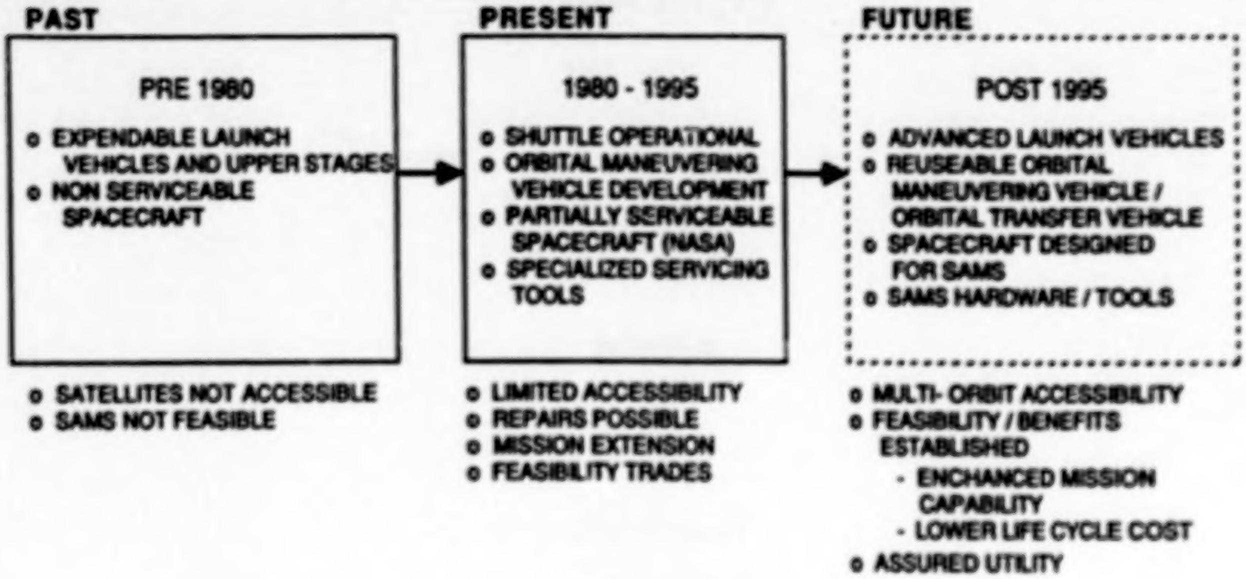
BACKGROUND

SAMS DEFINITIONS

SPACE

o ASSEMBLY:	CONSTRUCTION, ALIGNMENT, AND CALIBRATION
o MAINTENANCE:	TEST/CHECKOUT, MODULE REPLACEMENT, REPAIR, AND MODIFICATION
o SERVICING:	CONSUMABLE RESUPPLY

EVOLUTION OF SAMS



PAST

PRE 1980

- o EXPENDABLE LAUNCH VEHICLES AND UPPER STAGES
- o NON SERVICEABLE SPACECRAFT

PRESENT

1980 - 1995

- o SHUTTLE OPERATIONAL
- o ORBITAL MANEUVERING VEHICLE DEVELOPMENT
- o PARTIALLY SERVICEABLE SPACECRAFT (NASA)
- o SPECIALIZED SERVICING TOOLS

FUTURE

POST 1995

- o ADVANCED LAUNCH VEHICLES
- o REUSEABLE ORBITAL MANEUVERING VEHICLE / ORBITAL TRANSFER VEHICLE
- o SPACECRAFT DESIGNED FOR SAMS
- o SAMS HARDWARE / TOOLS

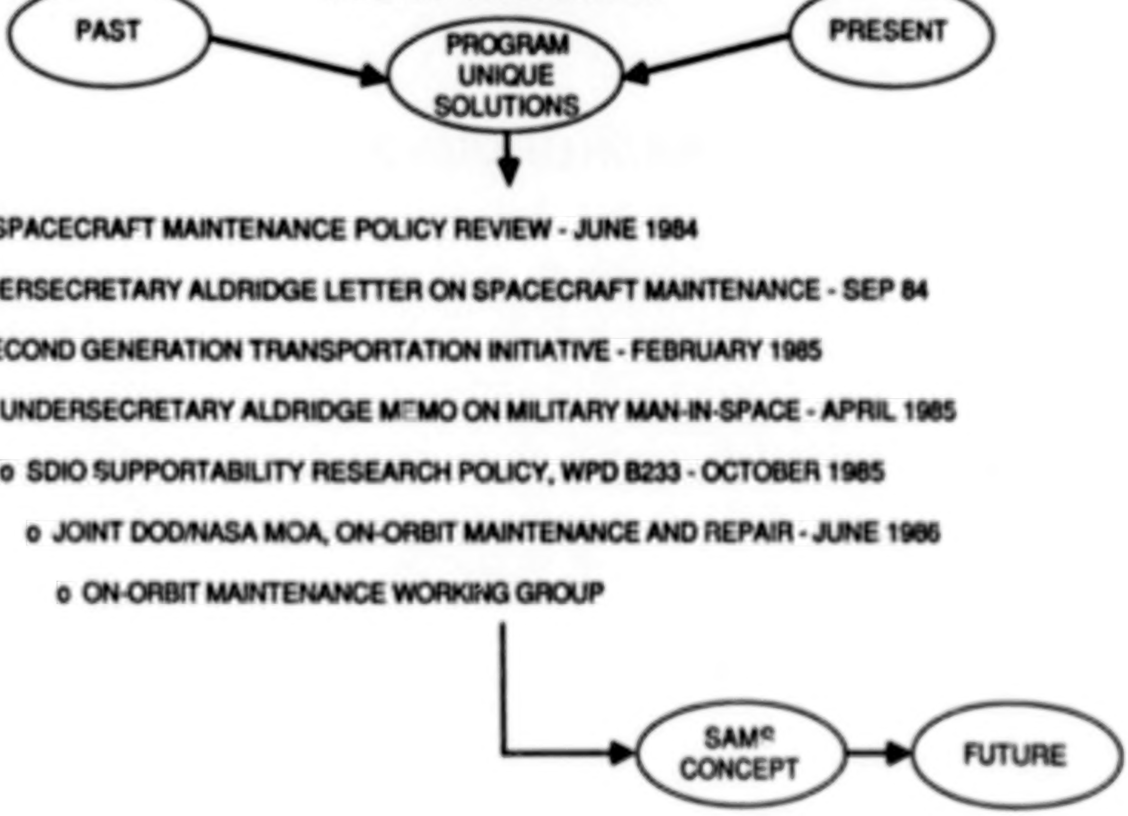
- o SATELLITES NOT ACCESSIBLE
- o SAMS NOT FEASIBLE

- o LIMITED ACCESSIBILITY
- o REPAIRS POSSIBLE
- o MISSION EXTENSION
- o FEASIBILITY TRADES

- o MULTI- ORBIT ACCESSIBILITY
- o FEASIBILITY / BENEFITS ESTABLISHED
  - - ENCHANCED MISSION CAPABILITY
  - - LOWER LIFE CYCLE COST
- o ASSURED UTILITY

ACCESSIBLE: REACH AND PERFORM SAMS OPERATIONS ON SPACECRAFT

POLICY DIRECTIVES



PAST

PRESENT

PROGRAM UNIQUE SOLUTIONS

- o USAF SPACECRAFT MAINTENANCE POLICY REVIEW - JUNE 1984
  - o UNDERSECRETARY ALDRIDGE LETTER ON SPACECRAFT MAINTENANCE - SEP 84
    - o SECOND GENERATION TRANSPORTATION INITIATIVE - FEBRUARY 1985
      - o UNDERSECRETARY ALDRIDGE MEMO ON MILITARY MAN-IN-SPACE - APRIL 1985
        - o SDIO SUPPORTABILITY RESEARCH POLICY, WPD B233 - OCTOBER 1985
          - o JOINT DOD/NASA MOA, ON-ORBIT MAINTENANCE AND REPAIR - JUNE 1986
            - o ON-ORBIT MAINTENANCE WORKING GROUP

SAMS CONCEPT

FUTURE

SAMS GOALS

- o DEFINE AND ESTABLISH SAMS CAPABILITIES TO MEET REQUIREMENTS FOR:
  - IMPROVED SPACE SYSTEMS
    - -- CAPABLE
    - -- FLEXIBLE
    - -- RESPONSIVE
    - -- AFFORDABLE

SAMS CONCEPT

SAMS ROADMAP

INITIAL SAMS CONCEPT DEFINITION

SAMS CONCEPTS (1986-1991)

- o INITIAL SAMS STUDY (CURRENT EFFORT)
- o PROOF-OF-CONCEPT HARDWARE / TECHNOLOGY DEMONSTRATIONS
- o INTEGRATED IMPLEMENTATION APPROACH

INITIAL DEVELOPMENT

TRANSITION TO INITIAL SUPPORT CAPABILITY (ISC) (1989-1995)

- o SAMS FULL SCALE ENGINEERING DEVELOPMENT
- o VERIFICATION/VALIDATION
- o SAMS ISC - 1995

FULL CAPABILITY

TRANSITION TO FULL SUPPORT CAPABILITY (FSC) (1995-2010)

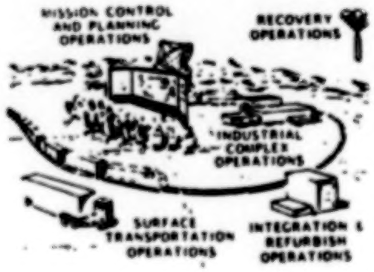
- o OPERATIONAL SAMS SYSTEMS
- o HARDWARE / TOOLS
- o SAMS FSC - 2010

SAMS APPROACH

- o INTEGRATED APPROACH
  - - DoD
  - - NASA
  - - TECHNOLOGIST / DESIGNER / USER INTERACTION
- o AVOID DUPLICATION OF EFFORT
- o ASSESS IMPACT IN ALL AREAS:

o SPACE

o TRANSPORTATION


MISSION CONTROL AND PLANNING OPERATIONS
RECOVERY OPERATIONS
INDUSTRIAL COMPLEX OPERATIONS
SURFACE TRANSPORTATION OPERATIONS
INTEGRATION & REFURBISH OPERATIONS

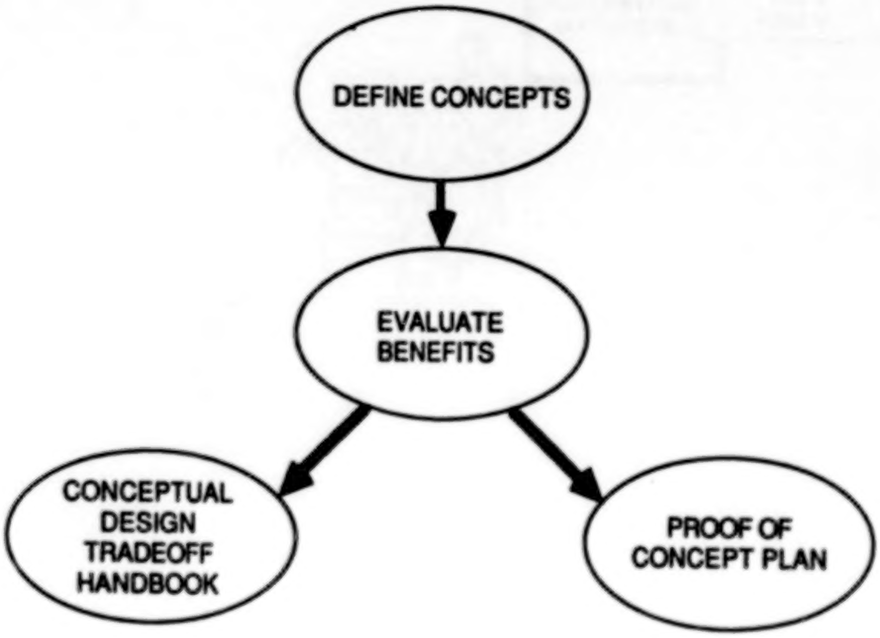
o GROUND

SAMS STUDY

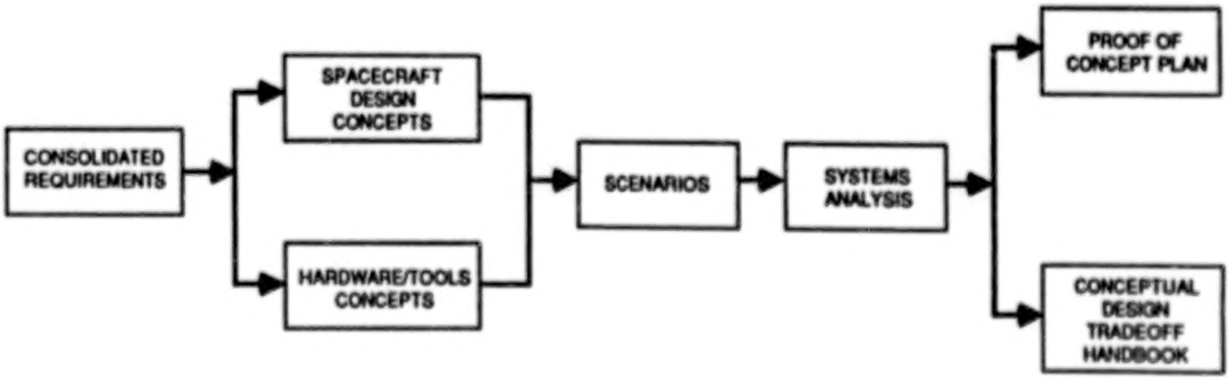
SAMS STUDY DESCRIPTION

- o OBJECTIVES
- o STUDY APPROACH
- o ADVISORY PANEL
- o SCHEDULE / MILESTONES
- o FUNDING

OBJECTIVES



SAMS STUDY APPROACH


CONSOLIDATED REQUIREMENTS
SPACECRAFT DESIGN CONCEPTS
HARDWARE/TOOLS CONCEPTS
SCENARIOS
SYSTEMS ANALYSIS
PROOF OF CONCEPT PLAN
CONCEPTUAL DESIGN TRADEOFF HANDBOOK

CONSOLIDATED REQUIREMENTS

SPACE TRANSPORTATION ARCHITECTURE STUDY (STAS) MISSION MODEL

SAMS STUDY REQUIREMENTS ANNEX
- o DoD
- o NASA

TECHNOLOGIST DESIGNER / USER INTERACTION

INTEGRATED SAMS REQUIREMENTS

REPRESENTATIVE NEAR / FAR-TERM MISSION MODEL

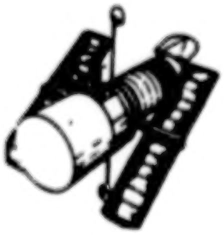
DESIGN REFERENCE MISSIONS (DRMs)

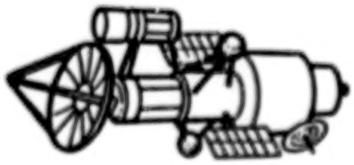
SPACECRAFT DESIGN CONCEPTS

DESIGN REFERENCE MISSIONS

PREVIOUS / CURRENT DESIGN CONCEPTS

TECHNOLOGIST/ DESIGNER / USER INTERACTION





STANDARDIZED MODULARIZED DESIGN APPROACHES

STANDARDIZED INTERFACE REQUIREMENTS

DESIGN CONCEPT DEFINITIONS

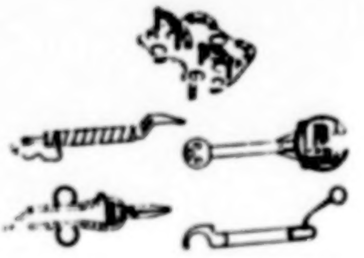
HARDWARE/TOOLS CONCEPTS

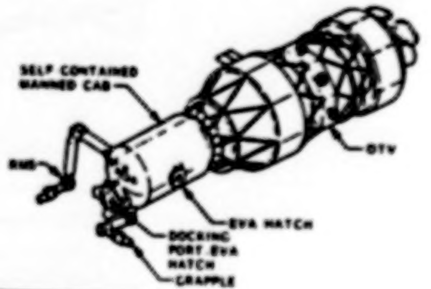
DESIGN REFERENCE MISSIONS

PREVIOUS / CURRENT EQUIPMENT WORK

SAMS CONCEPT DEFINITIONS

TECHNOLOGIST / DESIGNER / USER INTERACTION





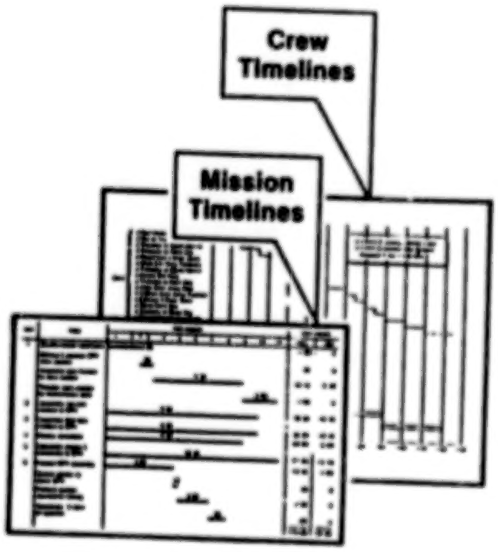
ON-ORBIT TASK DEFINITION

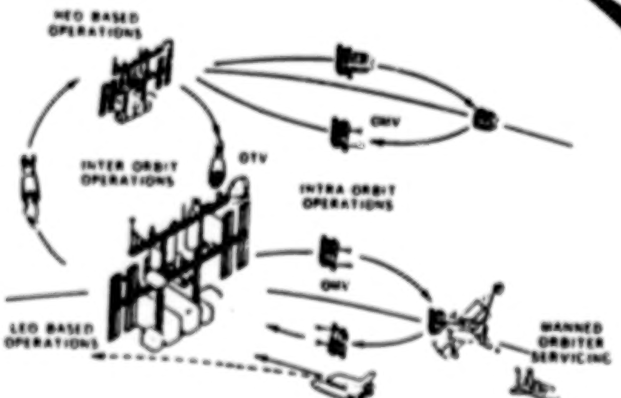
MAN / ROBOTIC TRADEOFF CONSIDERATIONS

HARDWARE / TOOLS DEFINITION

SCENARIOS

- o DESIGN REFERENCE MISSIONS
- o PREVIOUS / CURRENT OPERATIONAL CONCEPTS
- o HARDWARE / TOOLS DEFINITION
- o DESIGN CONCEPTS





- o OPERATIONAL CONCEPTS
- o SAMS SERVICING SCENARIOS
- o MANNED / REMOTE APPLICATIONS

SYSTEMS ANALYSIS

- SAMS STUDY SCENARIOS
- SPACECRAFT DESIGN CONCEPTS
- HARDWARE / TOOLS
- SELECTION CRITERIA

STUDY ANALYSIS
- FEASIBILITY
- HAZARDS
- SAMS CONCEPTS
- CONCEPT IMPACT

REQUIREMENTS SYNTHESIS & TECHNOLOGY NEEDS
- NEW CAPABILITIES
- CRITICAL PATHS

COST
- WBS
- SAMS ESTIMATES
- DRIVERS
- LIFE CYCLE BENEFITS

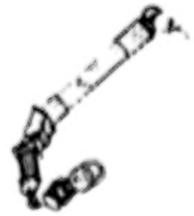
ALTERNATIVES DEFINITION
- TECHNOLOGY SHOPPING LIST

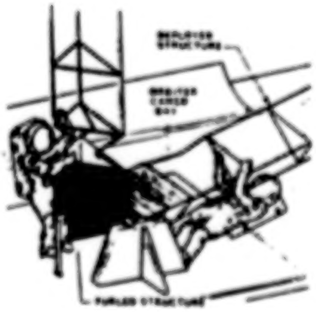
PROOF-OF-CONCEPT PLAN (CONCEPT EVALUATION)

PRELIMINARY SAMS SYSTEM CONCEPTS (AND TECHNOLOGIES)

PREVIOUS / CURRENT TECHNOLOGY DEMONSTRATION

INTEGRATION/COORDINATION WITH DoD / NASA / CIVIL DEMONSTRATIONS AND EXPERIMENTS



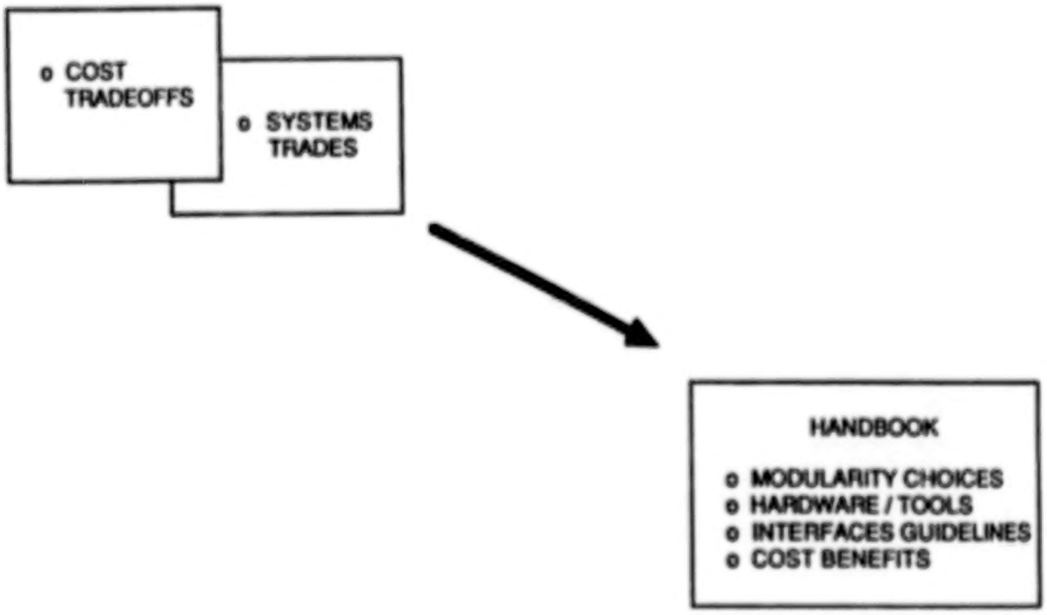


PROOF-OF-CONCEPT PROGRAM PLAN
- RECOMMENDED DEMONSTRATIONS
- ADDITIONAL ANALYSIS TASKS
- RECOMMENDED TECHNOLOGY DEVELOPMENTS

SAMS ADVISORY PANEL

AREA	FOCAL POINT
REQUIREMENTS	ROD LOCHMANN, AEROSPACE CORP.
S / C DESIGN	LT COL CHARLES BROWN, AFSC / SD (CGX)
HARDWARE / TOOLS	GORDON RYSAVY, NASA / JSC (EX2)
GOV'T ASTRONAUT REVIEW BOARD	LT COL JERRY ROSS, NASA / JSC (CB)
SAMS SCENARIOS / SYSTEM ANALYSIS	MAJ LOUISE JACKSON, AFSC / SD (XR)
LOGISTICS SUPPORTABILITY	COL JAMES GRAHAM, SDIO / SY
TECHNOLOGY	GEORGE LEVIN, HQ NASA / MT
POLICY / PROGRAMMATICS	LT COL RICK NELSON, HQ USAF / LE
STANDARDIZATION	LT COL GEORGE SAWAYA AFSC / SD (ALF)

CONCEPTUAL DESIGN TRADEOFF HANDBOOK



- o COST TRADEOFFS
- o SYSTEMS TRADES

HANDBOOK

- o MODULARITY CHOICES
- o HARDWARE / TOOLS
- o INTERFACES GUIDELINES
- o COST BENEFITS

RELATED STUDIES INTERACTION

STUDY	OPR / ORG	CONTRACTORS
SPACE TRANSPORTATION ARCHITECTURE STUDY	LT COL CORT DOROCHER AFSC / SD (CFP)	ROCKWELL GENERAL DYNAMICS MARTIN-MARIETTA BOEING
STANDARDIZATION STUDY	LT JANE DAUGHERTY AFSC / SD (YO)	ARINC
ON-ORBIT MAINTENANCE REPAIR STUDY (POLICY)	LT COL RICK NELSON HQ USAF / LEY	TBD
ORBITAL SPACECRAFT CONSUMABLES RESUPPLY SYSTEM (OSCRS) STUDY	NASA / JSC	FAIRCHILD MARTIN-MARIETTA ROCKWELL
SPACE STATION STUDY	NASA / JSC	RI, TRW, RCA, et al
ORBITAL MANEUVERING VEHICLE	NASA / MSFC	TRW
LOGISTICS INTEGRATION (LSA) STUDY	COL JIM GRAHAM SDIO / SY	TDB
SDI ARCHITECTURE STUDIES (PHASE II AND SARS)	SDIO	SAIC SPARTA TRW ROCKWELL MARTIN-MARIETTA, et al
KEW / DEW / SENSORS STUDIES	SDIO / AF / ARMY	VARIOUS

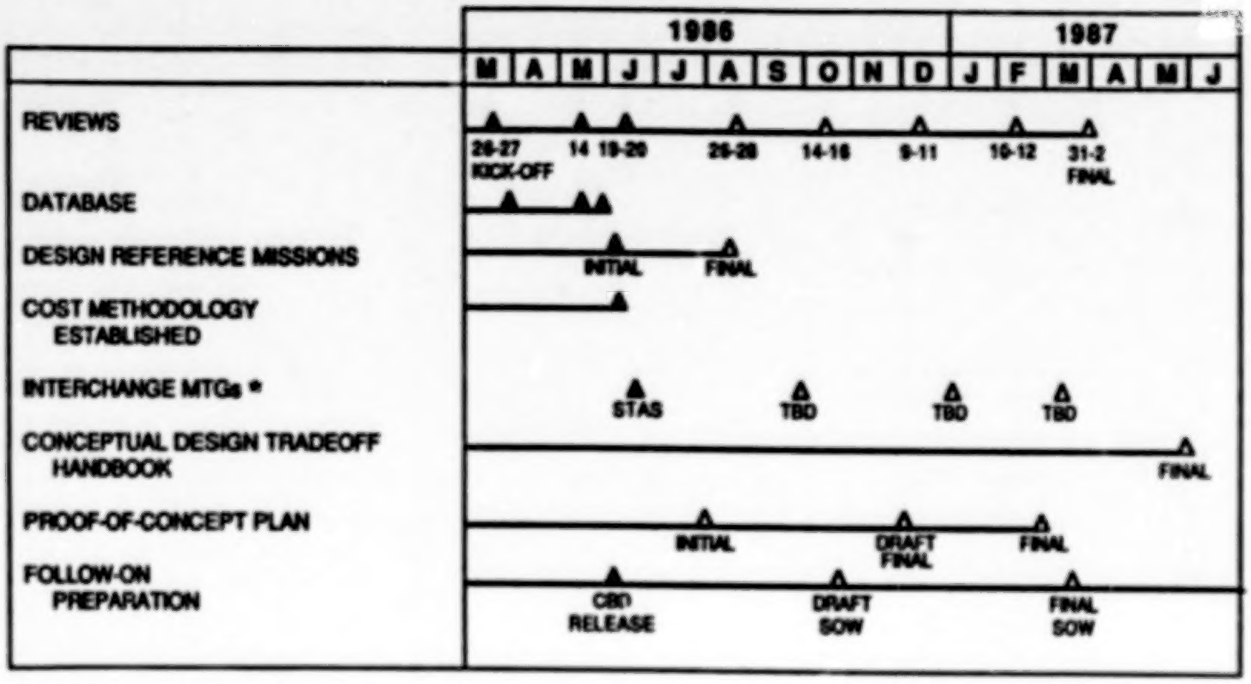
SAMS STUDY TEAM

GOVERNMENT

- o SPACE DIVISION (YO)
- o SDIO(SY)
- o HQ NASA(MT)

CONTRACTORS	
TRW	LOCKHEED
GRUMMAN	BOEING
Mc DONNELL DOUGLAS	HONEYWELL
BOOZ ALLEN HAMILTON	ILLINOIS INSTITUTE OF TECHNOLOGY
ADVANCED TECHNOLOGY	CARNEGIE MELLON
	LIFE SUPPORT SYSTEMS

SCHEDULE / MILESTONES



* POTENTIAL INTERCHANGES: STAS, LSA, SDI SYSTEMS ARCHITECTURE, TECHNOLOGY PROGRAMS

SUMMARY

- o EVOLVING NEED FOR SAMS
- o SAMS POLICIES ESTABLISHED
- o SAMS CONCEPT DEFINED
- o INITIAL STUDY UNDERWAY

↓

- o IMPROVED SPACE SYSTEM OPERATIONS
  - CAPABLE
  - FLEXIBLE
  - RESPONSIVE
  - AFFORDABLE

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TELEROBOTICS

Donna Pivirotto
Jet Propulsion Laboratory

This presentation summarizes NASA's future plans and current technology programs for telerobotics. Telerobotics involves electromechanical systems which have manipulation or mobility capability and are controlled by an operator. If the operator provides direct control through manipulation of master-slave servomechanisms and provides all the control intelligence, the system is referred to as teleoperated. If the operator provides only goals for an otherwise completely autonomous system, the system is a robot. In the fairly near term systems will be somewhere in between, will combine teleoperated and autonomous modes, and are therefore called telerobots.

Telerobots will be used for assembly and servicing in earth orbit and will operate from the space shuttle, the space station or, eventually, in high orbits from an orbit transfer vehicle (OTV). These telerobots will initially be attached to a host vehicle, such as the shuttle, but will be able to free-fly by the year 2000. These earth orbiting telerobots are likely to be somewhat anthropomorphic, at least initially, including two arms with dextrous end effectors, vision and force/torque sensing, and some level of artificial intelligence. Their primary mode will be to perform tasks designed for space-suited astronauts. Other telerobotic manipulators will have large crane-like arms (such as the shuttle remote manipulator system) for manuevering massive objects or supporting dextrous telerobots.

Telerobots will be used in planetary exploration to rove over planetary surfaces, initially most likely on Mars. These rovers may roll, fly or walk. They will collect and analyze geological samples and return the samples to a launch vehicle for return to earth orbit. They may be operated from earth by means of predetermined paths and thus travel slowly, or they may be intelligent enough to determine their own paths to interesting places and travel there while avoiding obstacles.

NASA OAST's telerobotic technology development is currently being integrated by the Jet Propulsion Laboratory in a series of demonstrations focused on multi-armed telerobots for dextrous manipulation. The demonstrations integrate technologies in operator interface (displays and

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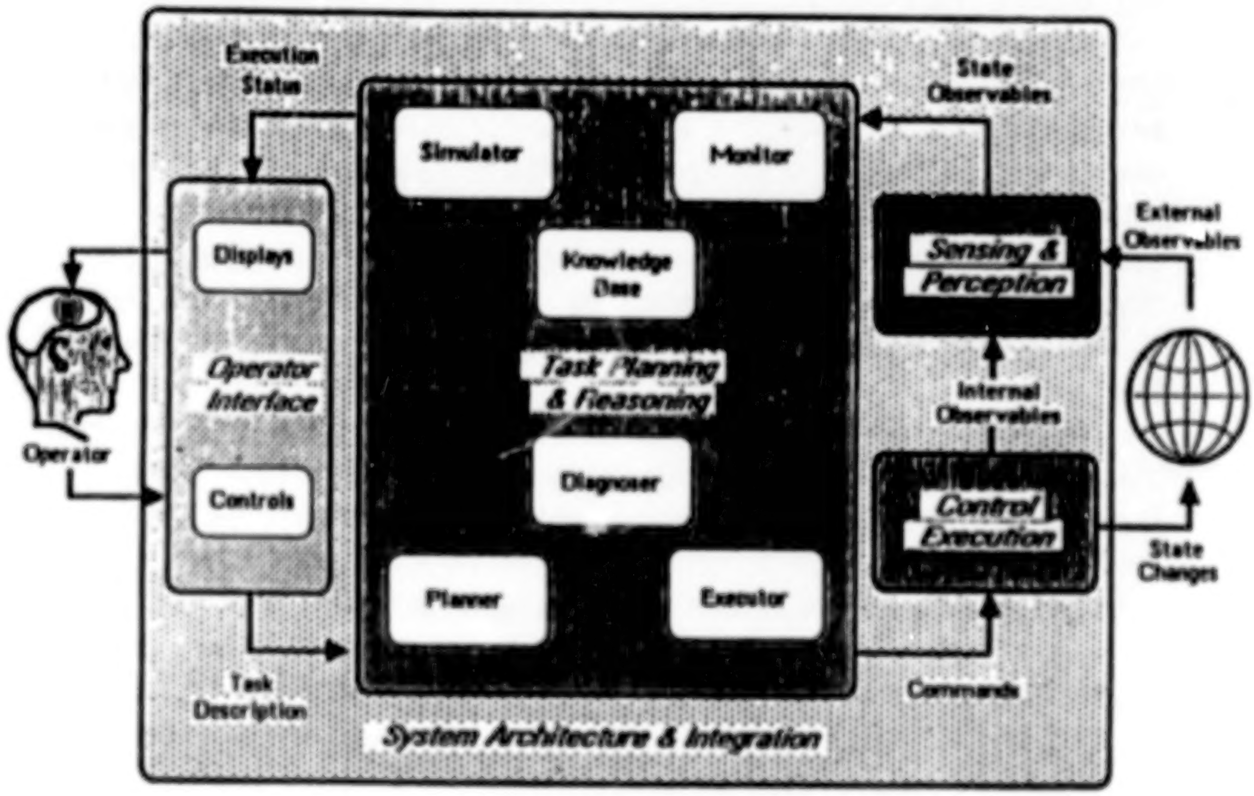
controls), sensing systems (vision and force/torque), task planning and reasoning (including artificial intelligence), control execution (mechanization and control of multiple manipulators and dextrous end effectors), and system architecture and integration (including executive and run-time control systems which integrate the control of the other elements). Issues of flight-qualified computers for telerobots are beginning to be investigated, and OAST is funding a modest program in flight symbolic and general purpose processors.

The military's current active involvement in telerobotics is primarily focussed on ground applications (e.g. DARPA's autonomous land vehicle program). However, joint planning efforts which include space telerobotics are being initiated with NASA in response to the president's directives for investigation of a new generation of launch vehicles and the space defense initiative.

Architecture for an Automated System



SPACE TELEROBOTICS

1987 DEMONSTRATION

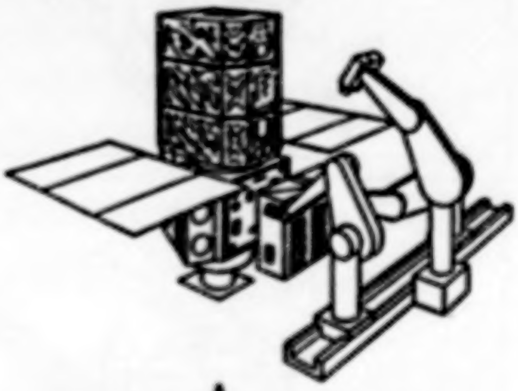
STATIONARY ROBOT, SIMPLE SPACECRAFT SERVICING TASKS, SUPERVISORY CONTROL

TECHNICAL ADVANCES

- SPACE SERVICING PRODUCTIVITY IMPROVEMENT
- DUAL-ARM COOPERATION
- MANUAL/POWER TOOL HANDLING

CONTROL STATION

- STEREO DISPLAYS
- TWO-ARM BILATERAL FORCE - POSITION CONTROL
- VOICE RECOGNITION/SYNTHESIS
- INTERACTIVE TASK PERCEPTION
- OFF-LINE INTERACTIVE PLANNING



RUN TIME CONTROL/PERCEPTION SYSTEM

- AUTOMATIC STEREO TASK FRAME ACQUISITION AND TRACKING
- AUTOMATED SYSTEM CONTROL AND SEQUENCING
- AUTONOMOUS/INTERACTIVE TASK EXECUTION AND MONITORING
- TELEOPERATOR CONTROL AS REQUIRED

NASA SPACE TELEROBOT LABORATORY DEMONSTRATION SEQUENCE

(ROBOT INTELLIGENCE, AUTONOMY AND TASK COMPLEXITY INCREASE OVER TIME)

- 1987 - STATIONARY ROBOT, SIMPLE SPACECRAFT SERVICING TASKS, SUPERVISORY CONTROL

  STATIONARY TWO-ARM TELEROBOT PERFORMS KNOWN SIMPLE TASKS ON COOPERATIVE SPACECRAFT USING HAND AND POWER TOOLS. LIMITED AUTONOMY

- 1990 - MOBILE ROBOT, SPACECRAFT SERVICING/RETRIEVAL, EXECUTIVE CONTROL

  MOBILE MULTIARM ROBOT PERFORMS KNOWN SIMPLE TASKS ON COOPERATIVE SPACECRAFT. LIMBER ARM INTERACTIVELY ACQUIRES AND DESPINS SPACECRAFT

- 1993 - SPACE SERVICING AND ASSEMBLY

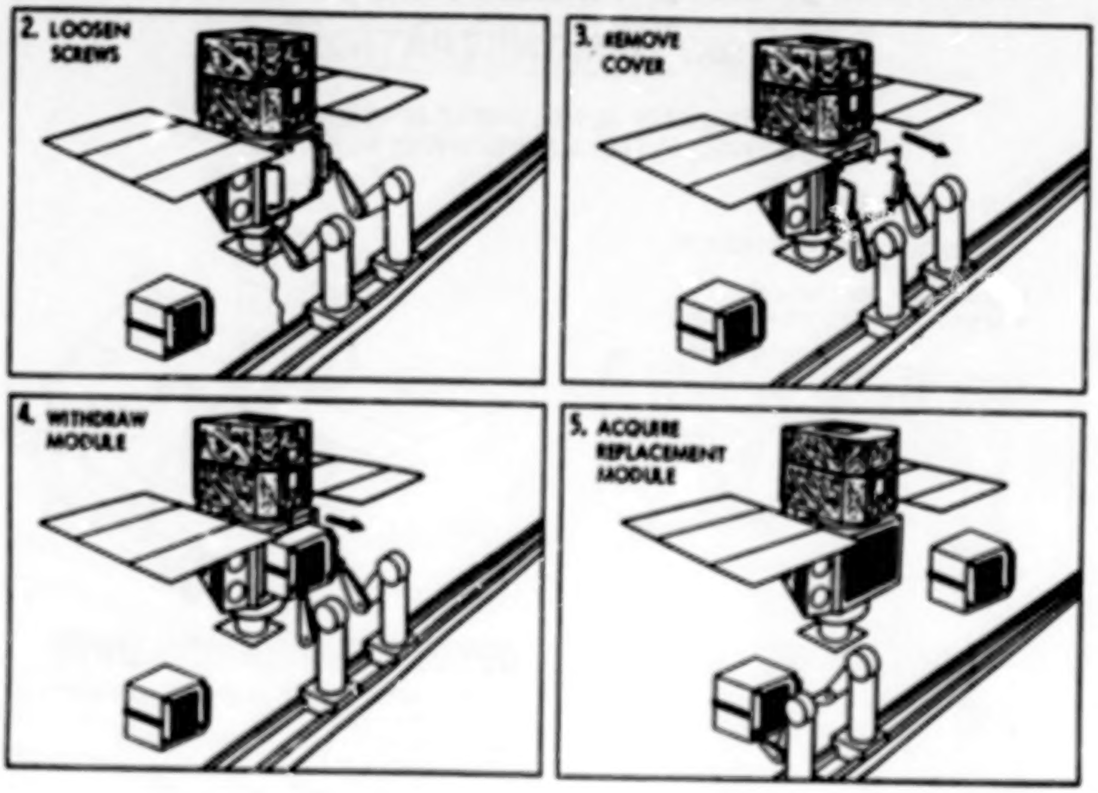
  MOBILE MULTIARM ROBOT PERFORMS MODERATELY COMPLEX SERVICING AND ASSEMBLY TASKS INVOLVING MULTIPLE ELEMENTS

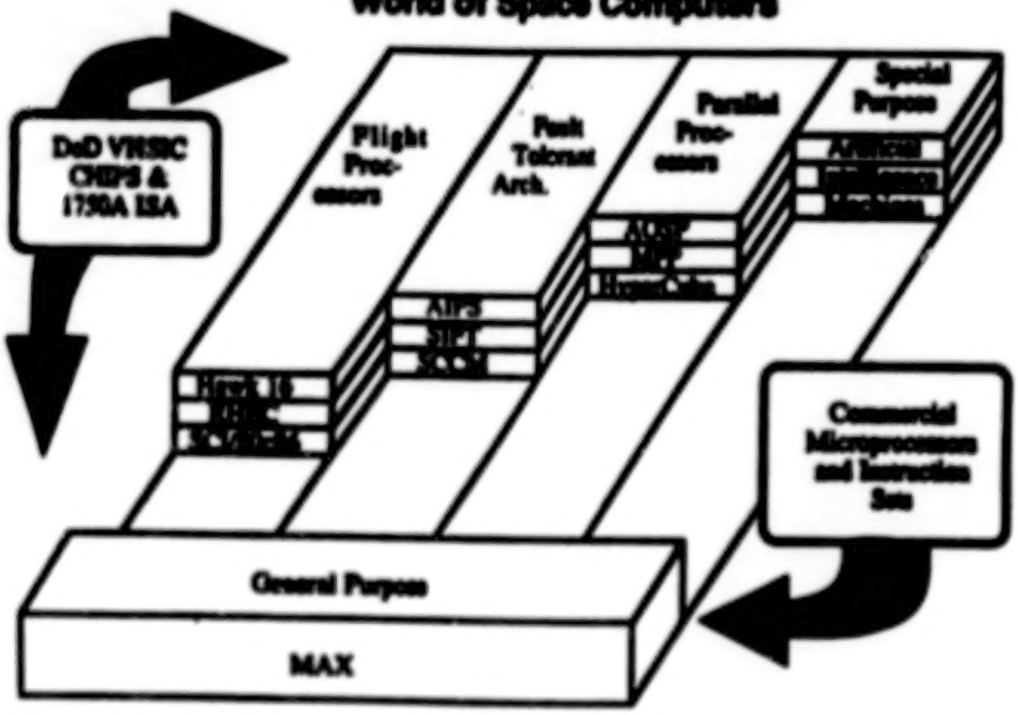
- 1996 - UNPLANNED REPAIR REQUIRING FABRICATION

  MOBILE, MULTIARM ROBOT INSPECTS, TESTS, AND REPAIRS DAMAGED STRUCTURAL AND MECHANICAL ELEMENTS. TASK INVOLVES DISASSEMBLY, CUTTING, AND MINOR FABRICATION

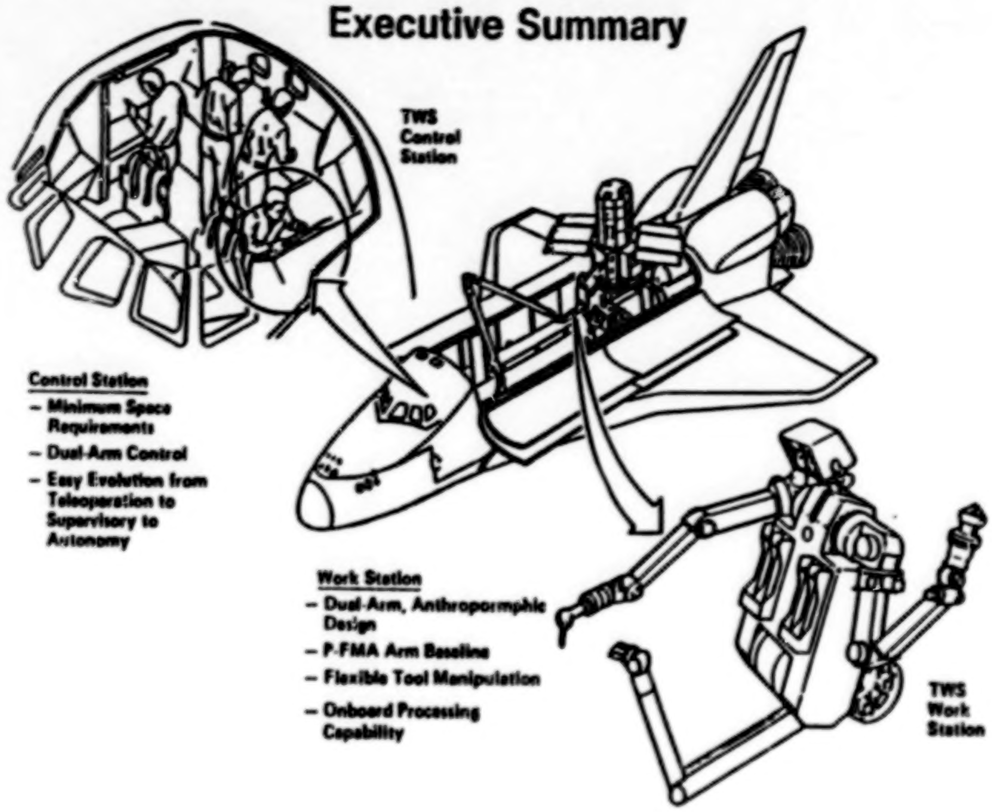
- 2000 - COOPERATIVE ROBOTS, COMPLEX GOAL DRIVEN TASKS

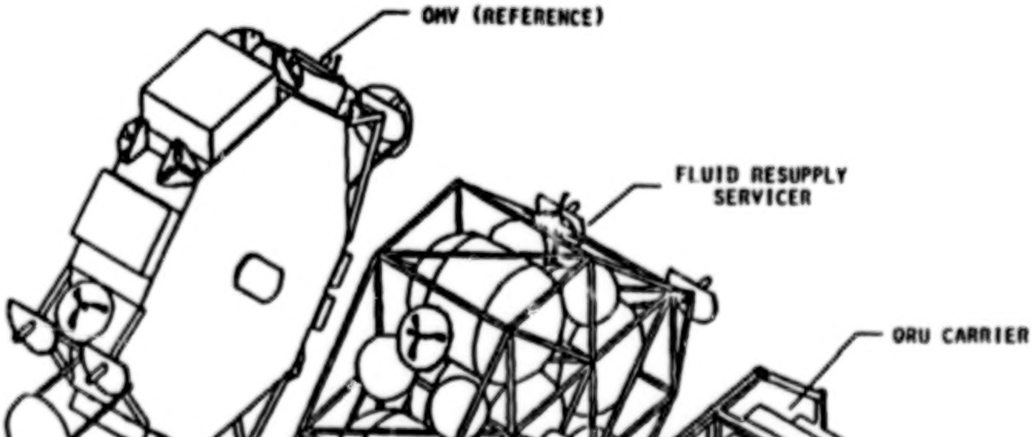
  COOPERATING MOBILE TELEROBOTS PERFORM COMPLEX TEMPORARY AND PERMANENT REPAIRS OF DAMAGED ELEMENTS USING AUXILIARY SUPPORTS, GUIDES, AND POWER TOOLS. PERIODS OF AUTONOMY MEASURED IN MINUTES


PROTOTASK EXECUTION SEQUENCE - MODULE CHANGEOUT


World of Space Computers

Executive Summary


TWS Control Station
Control Station
– Minimum Space Requirements
– Dual-Arm Control
– Easy Evolution from Teleoperation to Supervisory to Autonomy
Work Station
– Dual-Arm, Anthropormphic Design
– P-FMA Arm Baseline
– Flexible Tool Manipulation
– Onboard Processing Capability
TWS Work Station



SMART FRONT END (SFE)
(SEPARATED ELEMENT VIEW)

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SPACE STATION ASSEMBLY/SERVICING CAPABILITIES

Joseph Joyce
NASA Lewis Research Center

SUMMARY

THE AIM OF THE SPACE STATION IS TO PLACE A PERMANENTLY MANNED SPACE STATION ON-ORBIT AROUND THE EARTH. IT RESPONDS TO PRESIDENT REAGAN'S DIRECTIVE STATED IN HIS STATE OF THE UNION MESSAGE ON JANUARY 25, 1986. THIS TALK FOCUSES ON THE CORE SPACE STATION. THE OTHER SPACE STATION PROGRAM ELEMENTS INCLUDE THE CO-ORBITING AND POLAR PLATFORMS.

THE SPACE STATION PROGRAM IS INTERNATIONAL IN SCOPE. CANADA, EUROPE, AND JAPAN ARE OUR PARTNERS. NOTE THE CANADIAN MOBILE SERVICING CENTRE SYSTEM WHICH SHOULD PLAY A ROLE IN PAYLOAD SERVICING.

THE PROGRAM IS NEARING THE CLOSE OF THE SYSTEM DEFINITION AND PRELIMINARY DESIGN PHASE. THE FINAL DESIGN AND DEVELOPMENT PHASE WILL BEGIN IN THE FIRST HALF OF 1987. THE FIRST SHUTTLE LAUNCH FOR SPACE STATION ASSEMBLY ON-ORBIT IS ESTIMATED FOR JANUARY 1993. THE BASELINE ASSEMBLY SEQUENCE IS SHOWN AND THE INITIAL OPERATING CAPABILITY FOR THE MANNED CORE STATION IS DESCRIBED.

TOPICS PERCEIVED TO BE IMPORTANT TO ON-ORBIT ASSEMBLY AND SERVICING ARE DISCUSSED. EXTRAVEHICULAR ACTIVITY (EVA) PERMITS HANDS-ON OPERATIONS BY CREW MEMBERS IN ALL UNPRESSURIZED AREAS OF THE SPACE STATION. EVA IS A LIMITED RESOURCE THAT HAS TO BE ALLOCATED FOR BEST RETURN. THE CUSTOMER SERVICING FACILITY PROVIDES PROTECTION AND MANIPULATION OF PAYLOADS. IT FACILITATES THE SERVICING OF PAYLOADS AND SATELLITES. THE CANADIAN MOBILE SERVICING CENTRE SYSTEM WILL BE A ROBUST TELEROBOTIC SERVICER OPERATING IN THE SPACE ENVIRONMENT. IT SHOULD BE CAPABLE OF ACCESSING THE SHUTTLE CARGO BAY TO RETRIEVE CARGO, AND TRANSPORTING CARGO TO THE APPROPRIATE SITE OF OPERATION. A FLIGHT TELEROBOTICS CAPABILITY WITH DEXTROUS MANIPULATOR ARMS IS PLANNED FOR DEVELOPMENT BY THE UNITED STATES.

THE AUTHOR, JOSEPH P. JOYCE, IS A MEMBER OF THE POWER SYSTEM INTEGRATION OFFICE WITHIN THE LEWIS RESEARCH CENTER SPACE STATION SYSTEMS DIRECTORATE. HE IS PROJECT MANAGER FOR SYSTEM REQUIREMENTS AND INTERFACES IN THE AREAS OF OPERATIONS. ALSO HE IS A MEMBER OF THE SPACE STATION OPERATIONS PANEL AND A MEMBER OF OPERATIONS ASSOCIATED INTEGRATED CONFIGURATION AND ANALYSIS PANELS.

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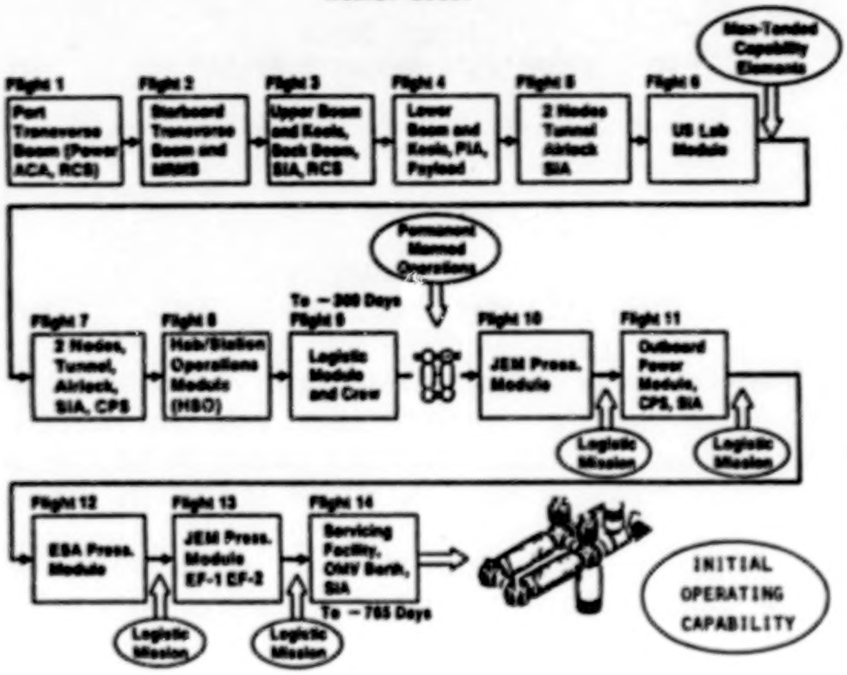
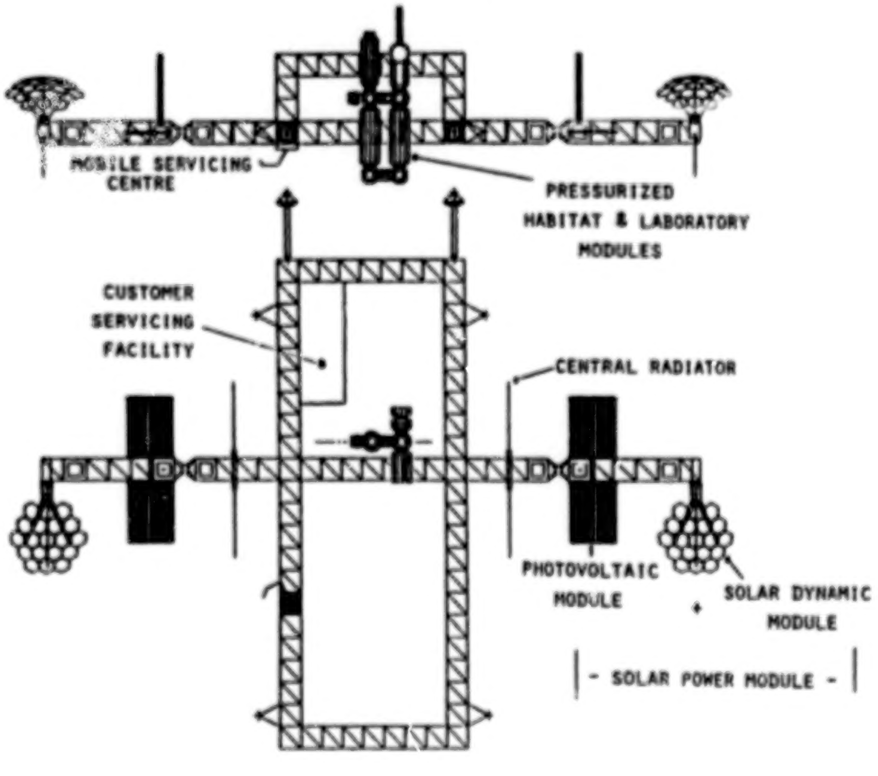
LAUNCH SCHEDULE
CORE SPACE STATION ASSEMBLY SEQUENCE
(MARCH 1986)


Man-Tended Capability Elements
Flight 1
Port Transverse Beam (Power ACA, RCS)
Flight 2
Starboard Transverse Beam and MRMS
Flight 3
Upper Boom and Keels, Back Boom, SIA, RCS
Flight 4
Lower Boom and Keels, PIA, Payload
Flight 5
2 Nodes Tunnel Airlock SIA
Flight 6
US Lab Module
Permanent Manned Operations
To − 300 Days
Flight 7
2 Nodes, Tunnel, Airlock, SIA, CPS
Flight 8
Hab/Station Operations Module (HSO)
Flight 9
Logistic Module and Crew
Flight 10
JEM Press. Module
Flight 11
Outboard Power Module, CPS, SIA
Logistic Mission
Logistic Mission
Flight 12
ESA Press. Module
Flight 13
JEM Press. Module EF-1 EF-2
Flight 14
Servicing Facility, OMV Berth, SIA
To − 765 Days
Logistic Mission
Logistic Mission
INITIAL OPERATING CAPABILITY

INITIAL OPERATING CAPABILITY
— CORE SPACE STATION —



ELECTRICAL POWER SYSTEM (EPS)

-- LEWIS RESEARCH CENTER RESPONSIBILITY --

SCOPE:

THE EPS INCLUDES POWER GENERATION, ENERGY STORAGE, POWER CONDITIONING, POWER SYSTEM CONTROL, POWER TRANSMISSION, POWER DISTRIBUTION, AND POWER MANAGEMENT. THE EPS COMPONENTS FOR GENERATION, STORAGE, CONDITIONING AND CONTROL ARE LOCATED IN THE SOLAR POWER MODULE FLIGHT ELEMENT.

DESCRIPTION:

SYSTEM - SOLAR DYNAMIC/PHOTOVOLTAIC HYBRID (STATION)
- PHOTOVOLTAIC (PLATFORMS)

PV ARRAY - SILICON, FLEXIBLE/DEPLOYABLE/RETRACTABLE DUAL
- BLANKET (COMMON STATION/PLATFORMS)

ENERGY STORAGE - NI/H_2 BATTERIES (PV)
- THERMAL

THERMAL - DEDICATED RADIATORS

DISTRIBUTION - 20KHz AC AT 208V

TOPICS RELATIVE TO ASSEMBLY AND SERVICING

- EXTRAVEHICULAR ACTIVITY
- CUSTOMER SERVICING FACILITY
- MOBILE SERVICING CENTRE SYSTEM
- ROBOTICS

EXTRAVEHICULAR ACTIVITY

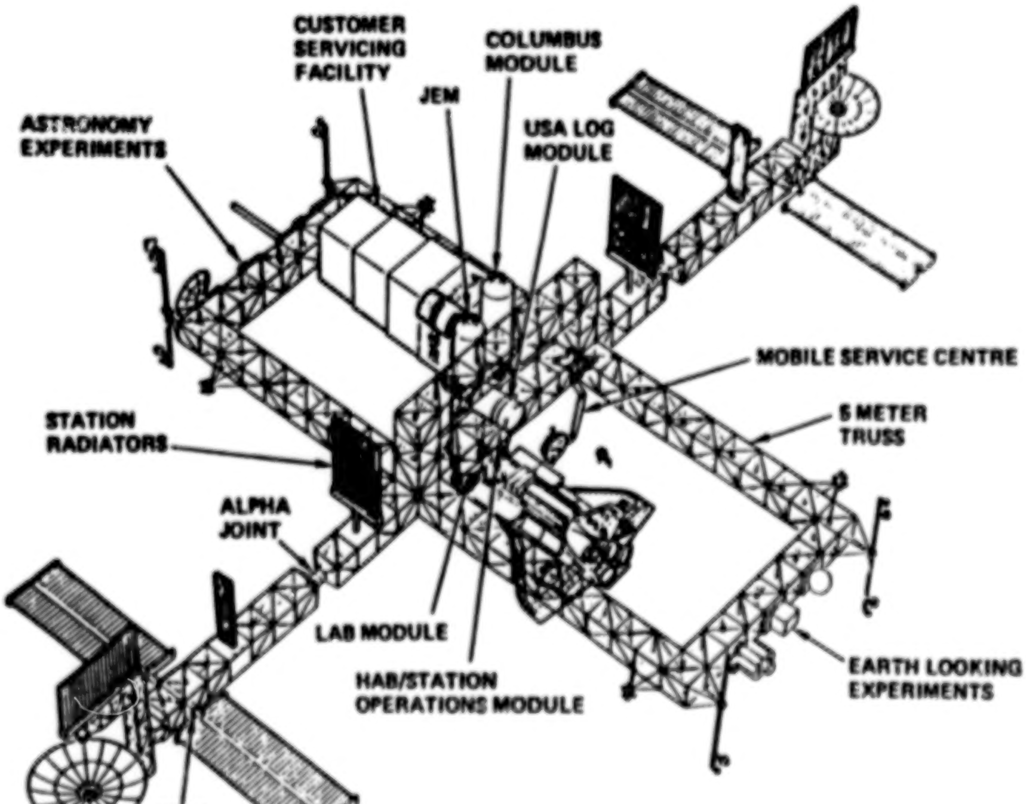
MAKEUP - LIFE SUPPORT (SPACE SUIT)
- AIR LOCK
- TRANSFER AIRLOCK
- TRANSLATION AIDS
- EQUIPMENT LIGHTING

USE - ASSEMBLY
- MAINTENANCE
- SERVICING
- REPAIR

COMPATIBILITY - MOBILE SERVICING CENTRE SYSTEM
- CUSTOMER SERVICING FACILITY

RESOURCE - LIMITED
- TWO CREWPERSONS PER EVA
- 640 TOTAL EVA HOURS PER YEAR, STS SUIT
(1872 TOTAL EVA HOURS PER YEAR, HIGH PRESSURE SUIT)

OPERATIONAL CORE SPACE STATION



CUSTOMER SERVICING FACILITY

-- GODDARD SPACE FLIGHT CENTER RESPONSIBLITY --

DEFINITION:

AN UNPRESSURIZED WORK SPACE FOR SERVICING AND ASSEMBLY OF FREE-FLYERS, ATTACHED PAYLOADS, PLATFORMS, AND OTHER CUSTOMER PAYLOADS.

PROVIDES:

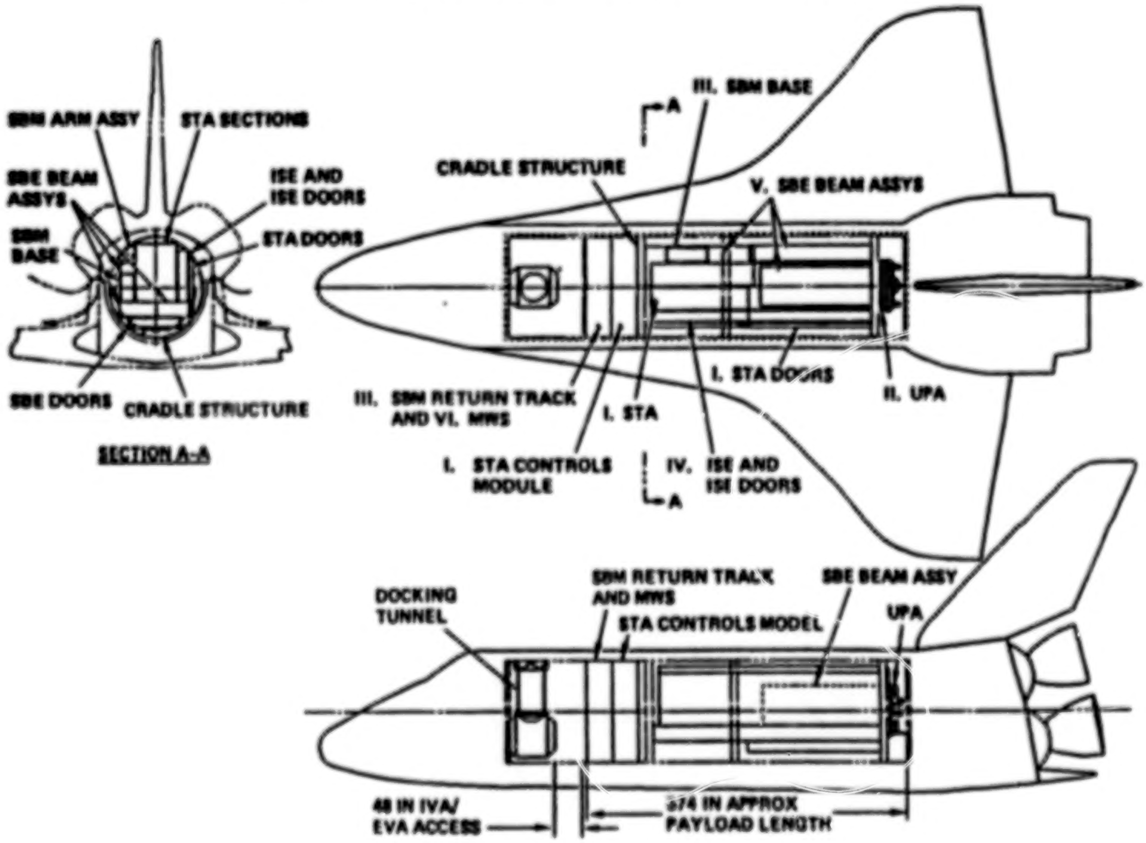
PROTECTION
MANIPULATION
STORAGE OF TOOLS AND ORBITAL REPLACEMENT UNITS
TEST AFTER SERVICE
ACCOMODATION FOR EVA

FACILITATES:

REPLACEMENT OF INSTRUMENTS
REPLACEMENT OF CONSUMABLES
CHANGE OUT OF ORU'S AND PAYLOADS
ASSEMBLY OF PAYLOADS

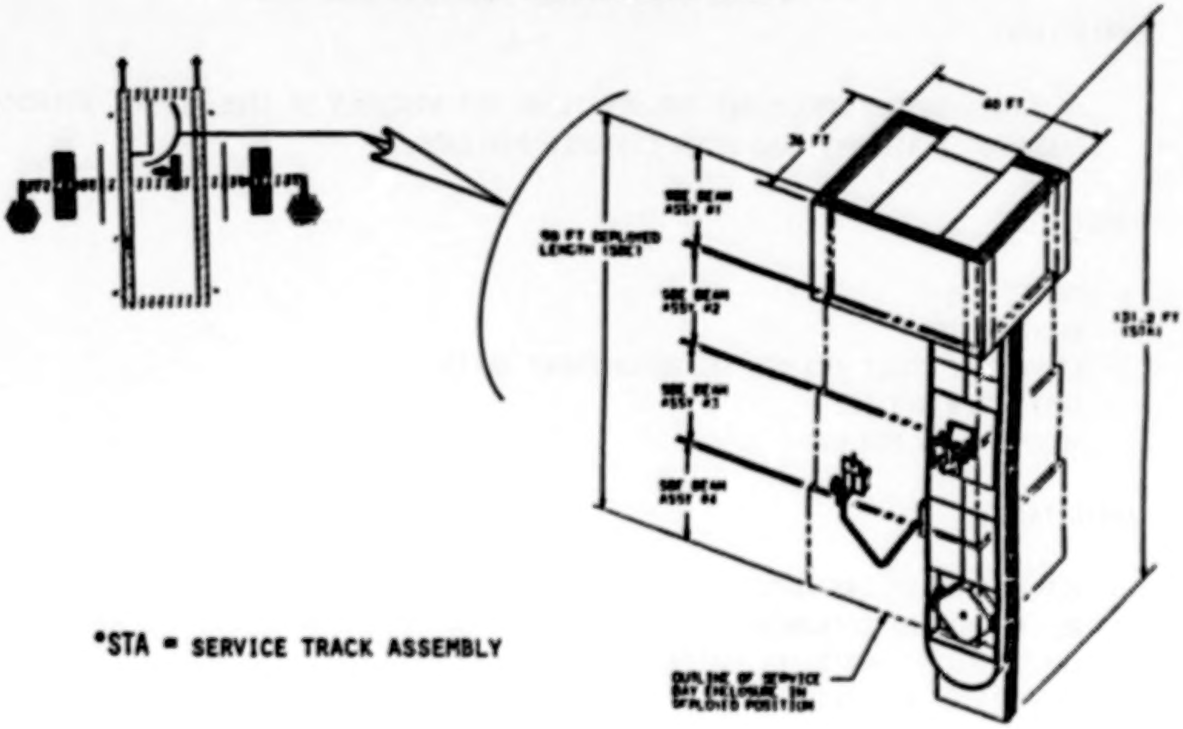
CUSTOMER SERVICING FACILITY

--CONCEPT FOR PACKAGING IN ORBITER CARGO BAY--



CUSTOMER SERVICING FACILITY

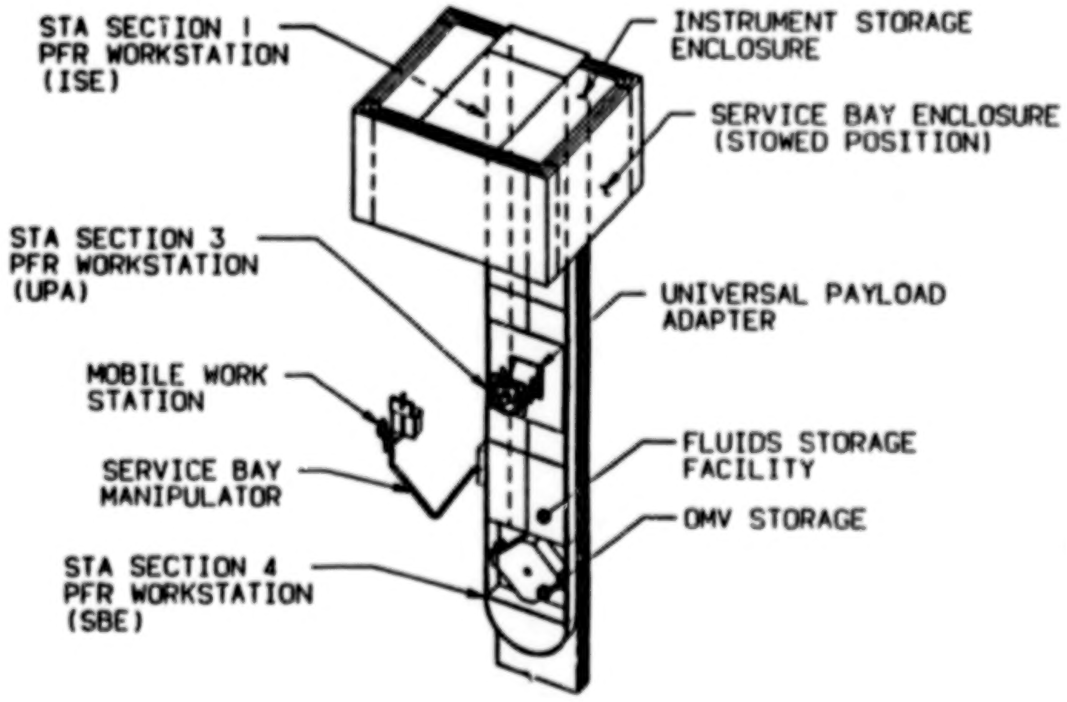
--SERVICE BAY ENCLOSURE (SBE)--



*STA = SERVICE TRACK ASSEMBLY

CUSTOMER SERVICING FACILITY

--SERVICE TRACK ASSEMBLY--



MOBILE SERVICING CENTRE SYSTEM

-- CANADIAN --

DEFINITION:

A ROBUST TELEROBOTIC SERVICER OPERATING IN THE SPACE ENVIRONMENT ON THE TRUSS STRUCTURE OF THE MANNED CORE SPACE STATION.

PROVIDES:

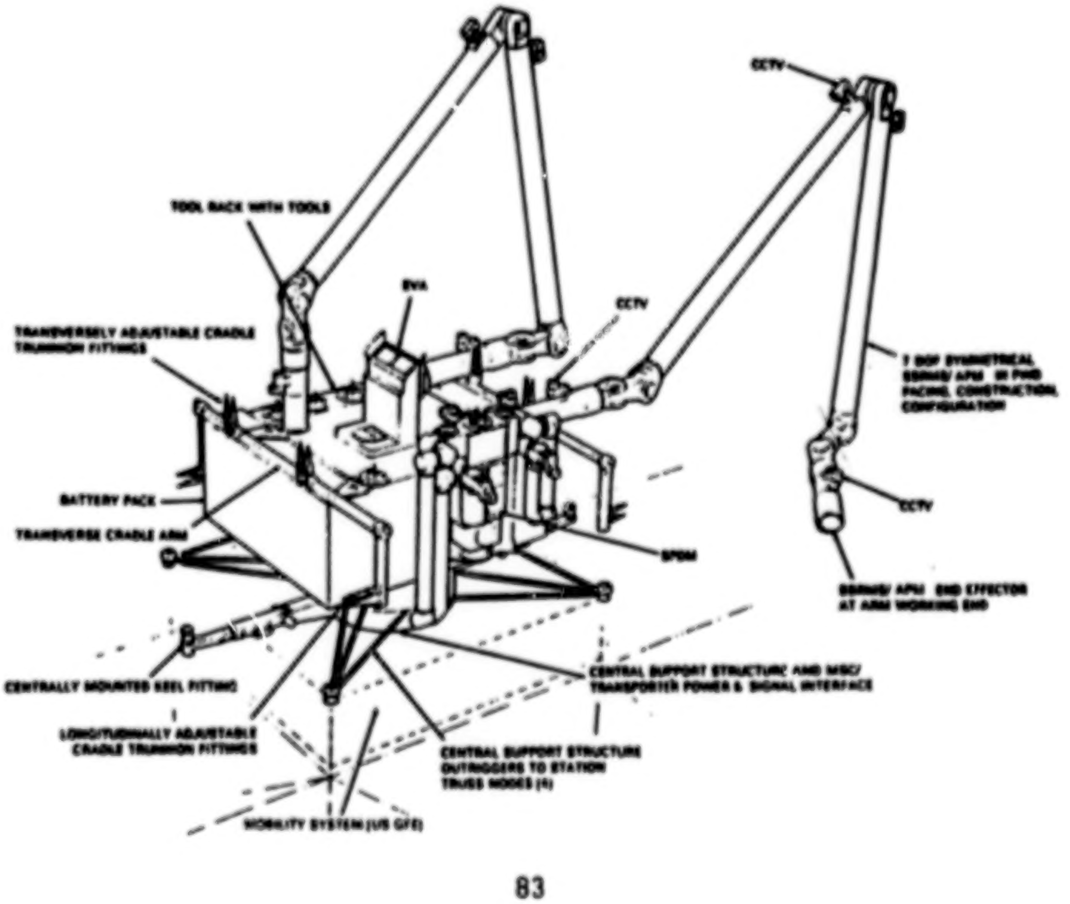
OPERATION ON BATTERIES OR DIRECT ELECTRICAL POWER SUPPLY
MANIPULATOR ARM(S)
ACCOMODATION FOR EVA
CONTROL FROM MANY LOCATIONS

CAPABILITIES:

ACCESS INTO SHUTTLE CARGO BAY
TRANSPORTATION
GRAPPLE A FREEFLYER
ASSEMBLY OPERATIONS
REPLACE ATTACHED PAYLOADS

MOBILE SERVICING CENTRE SYSTEM

--CANADIAN--


CCTV
TOOL RACK WITH TOOLS
EVA
CCTV
TRANSVERSELY ADJUSTABLE CRADLE TRUNNION FITTINGS
7 DOF SYMMETRICAL SSRMS/ APM IN FWD FACING, CONSTRUCTION, CONFIGURATION
BATTERY PACK
TRANSVERSE CRADLE ARM
CCTV
SPDM
SSRMS/ APM END EFFECTOR AT ARM WORKING END
CENTRALLY MOUNTED KEEL FITTING
CENTRAL SUPPORT STRUCTURE AND MSC/ TRANSPORTER POWER & SIGNAL INTERFACE
LONGITUDINALLY ADJUSTABLE CRADLE TRUNNION FITTINGS
CENTRAL SUPPORT STRUCTURE OUTRIGGERS TO STATION TRUSS NODES (4)
MOBILITY SYSTEM (US GFE)

ROBOTICS

-- USA --

DEFINITION:

FLIGHT TELEROBOTICS CAPABILITY WITH DEXTROUS MANIPULATOR ARMS AVAILABLE TO SUPPORT INITIAL SPACE STATION ASSEMBLY AND TO SERVE AS THE SMART FRONT END FOR THE ORBITAL MANEUVERING VEHICLE (OMV).

STATUS:

PLANNING UNDERWAY.
INITIAL FUNDING PROVIDED.

POTENTIAL CAPABILITIES:

MULTIPLE ARMS
FORCE AND TORQUE FEEDBACK
LIGHTING AND TV VIEWING.

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SPACECRAFT SYSTEMS WORKING GROUP REPORT

John Keigler, Chairman
RCA Astro-Electronics Division

Larry Rowell, Cochairman
NASA Langley Research Center

The Spacecraft Systems Group of the Spacecraft 2000 Workshop convened on the afternoon of Tuesday, 29 July 1986. Sessions were held that afternoon, and Wednesday all day and evening. Findings and recommendations were presented at the Thursday morning Plenary Session. A follow-up session was held on Thursday afternoon to incorporate findings of the various Subsystem Groups, and to make further recommendations to the Steering Committee.

The Spacecraft Systems Group was extremely large, consisting of twenty-eight members, including several members of the Steering Committee, who sat in on nearly all of the sessions. Dr. Jack Keigler, of RCA Astro Electronics Division, was Chairman, and Larry Rowell of NASA - Langley Research Center was Co-Chairman. The members participating in the group are listed in Attachment A.

The discussions were wide-ranging, reflecting the breadth of experience in the membership. Nevertheless, the group focused on the objectives of the workshop and on the issues assigned specifically to the Spacecraft Systems Group.

WORKSHOP OBJECTIVES

TO IDENTIFY THE CRITICAL NEEDS AND TECHNOLOGIES FOR SPACECRAFT OF THE 21ST CENTURY, AND TO RECOMMEND TECHNOLOGY DEVELOPMENT PROGRAMS AND IN-SPACE VALIDATION PROGRAMS AND POSSIBLE GOVERNMENT AND INDUSTRIAL ROLES AND PARTNERSHIPS.

SPECIFIC OBJECTIVE OF THE SPACECRAFT SYSTEMS GROUP

DETERMINE METHODOLOGY & GROUND RULES FOR SELECTION OF DESIGN CONCEPTS AND TECHNOLOGIES

ISSUES TO BE ADDRESSED BY THE GROUP

- Definition of user/commercial/government needs by function
    - Criteria for prioritization of needs
- Overall criteria for technology assessment, prioritization of needs

- System configuration drivers
  - Key trade studies - mass, life, power, cost, performance, etc.
- Space infrastructure interface
- Cost Drivers
  - Pros & cons of standardization
  - Manufacturing/test/serviceability/supportability

Ground rules announced at the initial Plenary Session were adhered to by the group while pursuing its objectives. These were that recommendations should:

- Exclude STS, SPACE STATION, and other payloads as solutions to the SPACECRAFT 2000 objective.
- Be independent of the SPACE STATION and OMV/OTV
- Provide technology payoff by the year 2000

As a result of the Tuesday afternoon session, several viewfoils were prepared and presented at the Wednesday morning plenary. These focused on the objectives, approach, methodology, criteria for technology assessment and prioritization, and mission drivers.

The working sessions of Wednesday afternoon and evening resulted in a refined set of thirteen viewfoils, which were presented at the final plenary on Thursday. These are introduced as Charts 1 through 12 in the text that follows.

Based on the objectives and ground rules, Chart 1, the group arrived at a consensus that the methodology should provide credible, quantified models for mission, costs, and reliability/availability upon which a technology assessment for enhanced payload mass fraction could be made. There was general agreement that reduced mass fraction of the spacecraft bus would enable a nearly one-to-one increase in payload mass fraction, and that most savings would be realized by improvements in propulsion, power, and structure/thermal technology. This viewpoint was presented in Chart 2.

A system methodology was developed by which a technology ranking could be accomplished, and presented as Chart 3. Mission models and requirements for future Low Earth Orbit (LEO), Geostationary Earth Orbit (GEO) and Planetary missions would first be developed. From this effort, general Systems and Subsystems

C-2

requirements would be defined for each mission category, and criteria for measurements of performance developed and utilized for prioritization. A cost and availability model would then be run for each mission to assess servicing, repairability, maintainability and operations considerations. This model must be fully developed, based on existing cost and availability models. Findings of the other spacecraft 2000 working groups could then be assessed against model results, with particular attention to the high pay-off subsystems. An iteration would result in a technology ranking which could then be used to prioritize technology experiments.

Transportation costs as a percentage of total system cost are not expected to change by the year 2000 due to the interacting effects of competition, technology improvements, fuel specific impulse increases, insurance costs, and increased reliability and safety requirements. Chart 4 therefore makes the point that increases in payload capability requires improvement in the technology and associated costs for the Spacecraft Bus and for the Operations and Maintenance functions.

Much discussion centered on the mission operations tasks and associated cost drivers. Chart 5 describes mission operations as the "missing subsystem", and defines its functions and what it does. Increases in spacecraft autonomy and reliability-availability would reduce operations and maintenance costs, and are therefore believed to be of equal importance to that of reducing spacecraft bus weight. Chart 6 was developed from an effort to identify the most important criteria for technology assessment and prioritization of needs. The five most important needs were identified, and relative weighting factors assigned based on general agreement of the membership. Reduction of Spacecraft Bus weight and reduction of operations and maintenance costs were considered equally important, and for the purpose of comparison, assigned a weighting factor of 10. As previously stated, technology increases in these areas will directly result in bigger payloads, with associated reductions in overall cost - a "bigger bang for the buck" in terms of payload capability in space.

Discussions of the group resulted in agreement that reduction in Spacecraft Bus weight will be most easily attained by better, lighter propulsion subsystems (and propellants), power subsystems, and structural/thermal subsystems. Increased synergism between subsystems will allow more streamlined data management, fewer sensors, lighter structure and reduced power. For example, sensors used for attitude control might also be used as reference for payloads and for alignment of a large flexible structure.

Reduction of operations and maintenance costs will be natural fallouts of increased spacecraft autonomy and reliability/availability. Spacecraft subsystems are gaining more autonomy with each new program, but true autonomy is many years away

unless a concerted effort is made to develop fault tolerant subsystems. Then there must also be a concerted effort to reduce the huge number of operations personnel now in place, particularly for military spacecraft. Geosynchronous satellites require far fewer people now, because the tasks of tracking, command loading, and pointing are straight forward and require only one station once in orbit. The major targets for autonomous subsystem development are low earth orbit satellites and, to a lesser degree, interplanetary spacecraft. Autonomous navigation subsystems which would automatically determine orbit parameters, accomplish pointing of the spacecraft and/or its payloads, and maintain structural alignments, would greatly reduce ground operations manpower.

A reduction of number and bandwidth of data links between the space and ground will be partially accomplished by improving spacecraft autonomy. A far greater savings would be realized by more extensive onboard processing of payload data. While data compression techniques have been developed to some extent, the tendency to collect, down-link, and process all data persists. Onboard processing would also reduce operations and maintenance costs, previously targeted as one of the highest priority items.

A weighting factor of only 7 was agreed upon because a reduction in number and bandwidth of data links will eventually become a necessity as the available spectrum becomes saturated. This in turn will force more and more onboard processing into spacecraft design.

Standardization of subsystems and interfaces would add greatly to savings in cost while improving reliability/availability. Connectors, processors and software, thrusters, sensors, batteries, etc., currently are of different design for every line of spacecraft. Much of this is because of competition between many spacecraft contractors and vendors. Although competition breeds improvements in quality and technology, there is a feeling that standardization can and should be accomplished whenever possible, and that studies should be made to determine the best way of accomplishing the goal. The provisions for using standardized subsystems, components, and interfaces could be imposed by government specifications and the statement of work for each new program. This was given a weighting factor of 5 when compared to other criteria.

Reduced costs of manufacturing and test is considered a given criteria, with a weighting factor of 3. This lower factor was agreed upon because there has been and should continue to be many incentives to accomplish the goal through innovative spacecraft design, and efficient manufacturing and test techniques.

Mission drivers to technology needs were categorized by mission type and launch/injection technique as shown in Chart 7. The mission types; Planetary, GEO or LEO, each have demands and criticality levels that are different in terms of technology issues. Chart 8 is the result of the Spacecraft Systems Group attempt to identify the importance of technology issues in each mission category. It stands alone in terms of generally identifying critical needs. However, much more intensive study is needed to quantify these needs as a basis for prioritizing technology development.

The National Space Needs summarized in Chart 9 are the result of evaluating the general technology issues, cost drivers, and polling the members of the panel. Of primary importance is the recognition that space assets needed for technology development have diminished over the past ten years because of reduced R&D budgets. Technology Development spacecraft, such as ATS and NIMBUS, no longer exist: virtually every program now focuses on current needs, not future needs. It was a strong opinion of the group that only orbital test platforms, dedicated to technology advancement, would enable and validate new technology.

Experiments to develop advanced large structures, attitude control subsystems and other subsystems can not possibly be conducted to the extent required on STS, on the Space Station or as piggyback on operational satellites because of the mutual impact between the experiment and host.

Certainly the kinds of technology development that are needed will require ground development and testing and much can be accomplished with the Space Station and STS, but only an orbital platform (or platforms) will enable the required total development needed.

The group compiled a list of candidate developments that an orbital test bed should be used for. These are listed in Chart 10, further classified as Technology Enabling or Technology Enhancing. Many were independently suggested by the various Subsystem Groups.

The characteristics of a Spacecraft 2000 were developed by the group and presented in Chart 11. These characteristics can be achieved by the deliberate, dedicated and funded technology development program recommended by the Spacecraft 2000 Workshop.

Recommendations of the Spacecraft Systems Group are summarized in Chart 12. The first recommendation is to develop system level analysis tools to assess subsystem technologies. These tools would be used in conjunction with the methodology for technology ranking previously discussed (Chart 3). Those developments selected could then be the subject of funded development, first with ground development and test, and then for development in space. Priority would be given to those identified as having the highest performance and cost benefits.

The second recommendation of the group is that NASA lead the development of a flexible, multidisciplinary Orbital Test Bed Program for the basic reasons listed on the chart. Test Beds should encompass one or more platforms which could be independent satellites or the Shuttle. Development experiments and tests would be systematically manifested onto and off of the test beds emphasizing co-utilization with compatible payloads.

On Thursday afternoon, the Spacecraft Systems group met to assess recommendations by the Subsystem Groups delivered at the morning plenary. It was agreed that their recommendations generally supported those of the Spacecraft Systems Group. Likewise the group concurred with Subsystem recommendations, but believes that design concepts and technology development program must first be well defined for prioritization and subsequent selection.

The methodology and ground rules have been generally outlined in this report and must be further developed. The selection process also requires development of adequate models to define costs, servicing, repairability, maintainability and operations characteristics.

Recommendations to the Steering Committee were:

1) NASA should solicit from industry and universities proposals for funded definition of in-space technology experiments. NASA Langley Research Center volunteered to perform this solicitation for proposals.

2) A separate solicitation should be made for proposals to develop in parallel the required system analysis tools to be used for evaluating and ranking of the proposed experiments.

Two 3-5 month (2-3 man-years) studies were recommended:

- **Develop a mission model (updated) which derives system and subsystem requirements that are then grouped into common technical (quantitative) requirements.**

- **Develop cost and availability models (decision criteria) for technology assessment.**

One study (3-4 month), perhaps by NASA in-house, was also recommended:

- **Introduce discipline technology trade-offs into two above models to determine ranking.**

At the end of these parallel studies, models should be exposed to industry review and critique.

NASA-HQ-OAST probably should lead this effort and select the best contractor.

3) After (1) and (2) are accomplished, an RFP should be issued to obtain the most suitable contractor to evaluate the proposed experiments based on the models and to provide a technology ranking OAST or NASA/LeRC could lead this effort.

4) Funded development of various experiments should then be accomplished on a competitive basis and contractors selected to define and construct the orbital test bed platforms, integrate and operate experiments, and provide launch capability and services.

These recommendations were given to the Steering Committee on the afternoon of 31 July 1986 and the Spacecraft Systems Group adjourned.

ATTACHMENT A
SPACECRAFT 2000 WORKSHOP
SPACECRAFT SYSTEMS GROUP MEMBERSHIP

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SPACECRAFT SYSTEMS GROUP

OBJECTIVE DETERMINE METHODOLOGY AND GROUND RULES FOR SELECTION OF DESIGN CONCEPTS AND TECHNOLOGIES

GROUND RULES

- EXCLUDE STS, SPACE STATION, PAYLOADS
- INDEPENDENT OF SPACE STATION & OMV / OTV
- TECHNOLOGY PAYOFF BY YEAR 2000

CHART 01

SYSTEMS METHODOLOGY

- CREDIBLE, QUANTIFIED MODELS FOR
  - MISSIONS
  - COSTS
  - RELIABILITY / AVAILABILITY
- TECHNOLOGY ASSESSMENT FOR ENHANCED PAYLOAD MASS FRACTION
  - PROPULSION
  - POWER
  - STRUCTURE / THERMAL

CHART 02

SYSTEMS METHODOLOGY FOR TECHNOLOGY RANKING

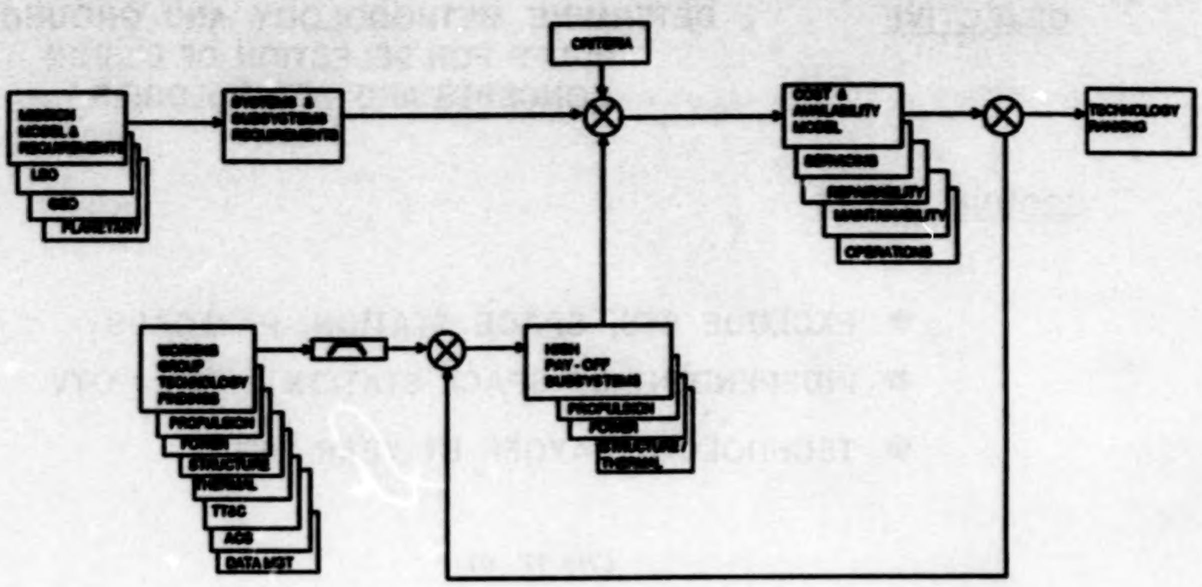

CHART 03

SYSTEM COST DRIVERS

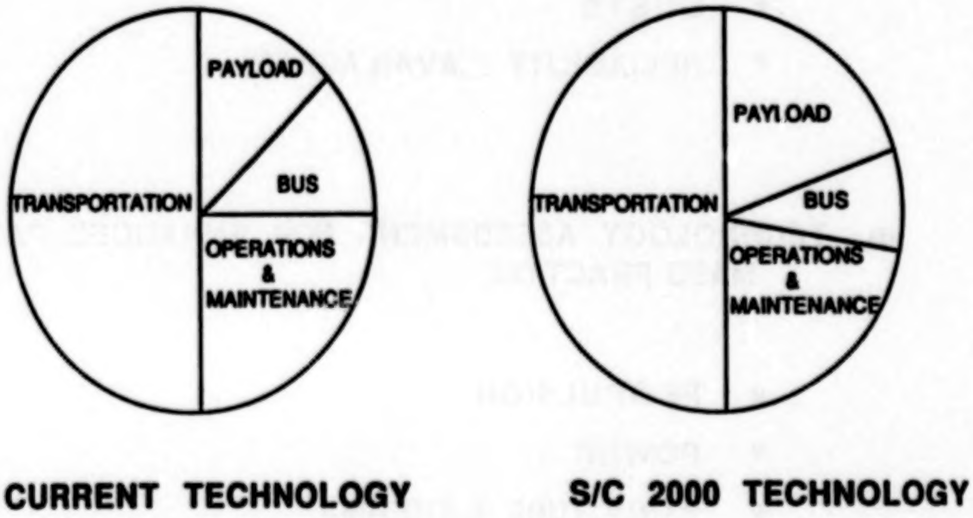

CHART 04

MISSION OPERATIONS - THE "MISSING SUBSYSTEM"

WHAT IS IT ?

- THE SOFTWARE AND HARDWARE NEEDED TO OPERATE AND CONTROL SPACE SYSTEMS
- A SUPER SUBSYSTEM CONSISTING OF MANY GROUND AND SPACE ELEMENTS PLUS COMMUNICATIONS LINKS

WHAT IT DOES.

- SUBSYSTEM INTEGRATION
- COMMAND AND CONTROL INTERFACES
- RESOURCE MANAGEMENT
- FAULT MANAGEMENT
- USER INTERFACES
- SERVICING SUPPORT

CHART 05

CRITERIA FOR TECHNOLOGY ASSESSMENT AND PRIORITIZATION OF NEEDS

	WEIGHTING FACTOR
• REDUCTION OF S/C BUS WEIGHT • PROPULSION, POWER, STRUCTURE • SYNERGISM (SUBSYSTEM)	10
• REDUCTION OF OPERATIONS AND MAINTENANCE COSTS • INCREASED S/C AUTONOMY • INCREASED RELIABILITY / AVAILABILITY	10
• REDUCTION OF DATA LINK DEMANDS • ON - BOARD PROCESSING	7
• STANDARDIZATION OF SUBSYSTEMS AND INTERFACES • INCLUDING SOFTWARE	5
• REDUCED COST OF MANUFACTURING AND TEST	3

CHART 06

MISSION DRIVERS TO TECHNOLOGY NEEDS

- **MISSION TYPE**
  - LEO
  - GEO
  - PLANETARY

- **LAUNCH AND INJECTION TECHNIQUE**
  - ELV VS SHUTTLE
  - SPACE STATION VS DIRECT
  - GROUND VS IN - SPACE ASSEMBLY

CHART 07

CRITICAL TECHNOLOGY AREAS

TECHNOLOGY ISSUES	GENERIC MISSION CATEGORIES		
CRITERIA	PLANETARY	GEO	LEO
WEIGHT	• MOST CRITICAL	• CRITICAL	• LEAST CRITICAL
OPERATION OR MAINTENANCE	• HI AUTONOMY DEMAND • EXPERT SYSTEM DRIVER • ALLOCATE FUNCTION TO SOFTWARE	• REDUCE GROUND DEPENDENCY • SMART SOFTWARE FOR TELEOPERATION	• REDUCE GROUND DEPENDENCY • USE SOFTWARE TO RELIEVE MAN
DATA	• IN SPACE LINKS NEEDED	• INTERFERENCE FROM MULTIPLE USERS	• BANDWIDTH DRIVER • ON BOARD DATA REDUCTION REQUIRED
INTERFACES & STANDARDS	• NOT CRITICAL	• STANDARDS FOR SERVICING • ON - ORBIT MAINTENANCE STANDARDS	• MODULAR SUBSYSTEMS • MAN & MACHINE INTERFACE STANDARDS • ON - ORBIT MAINTENANCE STANDARDS

CHART 08
1 OF 2

CRITICAL TECHNOLOGY AREAS

TECHNOLOGY ISSUES	GENERIC MISSION CATEGORIES		
CRITERIA	PLANETARY	GEO	LEO
REPAIR	• SELF - REPAIR • TREND ANALYSIS	• TELEROBOTICS	• DESIGN TOOLS FOR SUPPORT ABILITY • MAN SUPERVISE / MACHINE DO
ENVIRONMENTS			
INDUCED	• AVIOD CONTAMINATION OF SUBJECT	• AVIOD CONTAMINATION OF INSTRUMENTS	• IN SITU SERVICING DOCKING CONTAMINATION • DEBRIS
NATURAL	• HI LOADS/ SOLAR AREA	• EMI	• MATERIALS / ATOMIC OXYGEN • POLAR PLASMA / EMI

CHART 08
2 OF 2

NATIONAL SPACE NEEDS

- LOW COST, RELIABLE TRANSPORTATION
  - SYSTEM COST DRIVER
- ORBITAL TEST PLATFORMS
  - ENABLE NEW TECHNOLOGY
  - VALIDATE ADVANCED TECHNOLOGY
- LOW COST, LONG LIFE SPACECRAFT
  - MODULAR STANDARD INTERFACES
  - AUTONOMOUS OPERATION
  - REPAIRABLE / SERVICEABLE

CHART 09

TEST BED UTILIZATION

TECHNOLOGY ENABLING	TECHNOLOGY ENHANCING
HEAT PIPE / THERMAL STORAGE	LARGE DIAMETER N_2 O_2 DIAPHRAMS
TETHERED POWER / PROPULSION EXPERIMENTS	ELECTRIC PROPULSION DEVICES
CONTROL OF LARGE STRUCTURES	ADVANCED BATTERIES
TELEROBOTICS DEMONSTRATIONS	ADVANCED STELLAR SENSORS (< 1 ARC SEC)
CONTAMINATION STUDIES	AUTONOMOUS SYSTEM DEMOS
CRITICAL CLEANING	NUCLEAR POWER SUPPLY HANDLING
ENVIRONMENTAL INTERACTIONS	NEW SOLAR CELLS
TWO - PHASE FLUID PHENOMENA	HIGH POWER ELECTRICAL DISTRIBUTION & SWITCHING
CRYO REFRIGERATORS	

CHART 10

SPACECRAFT 2000 SYSTEM CHARACTERISTICS

- MODULAR CONSTRUCTION / STANDARD INTERFACES
    - INTERCHANGEABLE / REPAIRABLE
    - UPGRADEABLE
    - DEVELOPMENT COSTS REDUCED
- AUTONOMOUS SYSTEMS
    - REDUCED OPERATIONS COSTS
    - FAULT DETECTION / ISOLATION
    - RECONFIGURATION
    - REDUCED DATA LINK LOADS
- REPAIRABLE / SERVICEABLE SUBSYSTEMS
    - INCREASED SPACECRAFT LIFE
    - REDUCED CONSUMABLES MASS
    - RECONFIGURABLE HARDWARE

CHART 11

RECOMMENDATIONS & BENEFITS

DEVELOP SYSTEM LEVEL ANALYSIS TOOLS FOR SUBSYSTEM TECHNOLOGY ASSESSMENT

- EARLIEST IDENTIFICATION OF THE HIGHEST PERFORMANCE AND COST BENEFITS

DEVELOP A FLEXIBLE, MULTIDISCIPLINARY ORBITAL TEST BED CAPABILITY

- TECHNOLOGY RISK REDUCTION
- INSTILL NEW MOMENTUM IN TECHNOLOGY DEVELOPMENT
- ENCOURAGE COMMERICAL VIABILITY
- PROVIDE UNITED STATES SPACE TECHNOLOGY LEADERSHIP

CHART 12

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SYSTEM DEVELOPMENT WORKING GROUP REPORT

William Smith, Chairman
TRW Space and Technology Group

William Bifano, Cochairman
NASA Lewis Research Center

Introduction

The System Development Working Group's output was highly dependent upon the parallel working group sessions in the spacecraft system and subsystems areas. As such, a deliberate attempt was made to have working group members interact with the other working groups. However, due to the time lag of some of the other working groups' actions, the key technologies shown for analysis are as of late Wednesday afternoon of the workshop.

The charter of the System Development Working Group is shown in Figure 1. The objective of the System Development Working Group was to recommend an approach to technology validation and in-space system technology demonstration. In addition, this working group was charged with making a unique recommendation relative to the evolution of automation and robotics. The readers of this proceedings will note that automation and robotics really is distributed in a number of the working group reports. Therefore, the System Development Group decided to focus their attention on telerobotic evolution for the Spacecraft 2000 infrastructure.

The System Development Working Group carried the following assumptions through their working group deliberations:

1. No launch vehicle constraints
   - All the national launch systems capabilities are available.
2. STS and Space Station are available for use as in-space test beds.

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3. Orbital serviceability had reached maturity and was available.

4. NASA/DOD national test beds are available on a cooperative, non-interference basis.

In addition, the working group felt it should take advantage of existing and planned NASA and DOD in-space facilities and systems in conducting the proposed in-space testing.

The key issue in the System Development Working Group was: how do you get new technology introduced into systems without increasing program risk? The Spacecraft 2000 thrust must permit introduction of highly leveraged technology which is mature with well understood technical and programmatic risk.

Spacecraft 2000 Key Technologies

The Spacecraft 2000 key technologies in priority order are listed in Figures 2 and 3; there was a forced choice imposed by the System Development Working Group in that we asked each working group to give us their top three. In a few instances they coalesced on four recommended technology areas. As a reminder, there is the caveat of the time lag relative to the final disposition of the various working groups' technology listings.

Generic Spacecraft 2000 - Test Bed Philosophy

The need for a generic Spacecraft 2000 test capability presented by a member of the System Development Group, Jim Loos of Lockheed, was accepted as a working philosophy. Figure 4 represents the ground and space segment test philosophy which is integral to our recommendations.

Test Bed Requirements Analysis

The System Development Group performed a top level analysis of ground and in-space test requirements relative to the other working groups high priority technology areas. Figures 5 and 6 depict the summarization of that analysis. Under ground test capability, the "E" represents existing and "N" equals new. The in-space test requirements were analyzed around major capabilities of the Space Transportation System (STS), Space Station (SS), and Free Flyer (FF). The need for a space test free flyer capability became evident from this preliminary top level analysis.

Space Test Bed Characteristics

The System Development Working Group developed a list of key space test capability characteristics which are shown in Figure 7. Since the characteristics are self-explanatory, no further discussion is necessary.

Summary

The critical need, as shown in Figure 8, is the need for funding and testing as bridging support for Spacecraft 2000 highly leveraged technology to promote flight development introduction and acceptance. We need to make use of all existing test capabilities. However, we foresee critical needs to augment these capabilities to satisfy specific enabling technology validation and to flight qualify selected technologies.

Recommended Actions

Figure 9 summarizes the System Development Working Group's recommendations. We believe OAST has a unique NASA leadership opportunity to promote timely and effective technology transition.

Acknowledgements

Figure 10 lists the System Development Working Group membership. The working group would like to express its appreciation to LeRC and OAST for their foresight and leadership in conducting this timely workshop and to their NASA colleagues for their support.

SYSTEMS DEVELOPMENT W/G OBJECTIVE/ASSUMPTIONS/KEY ISSUES

OBJECTIVE:
- RECOMMEND APPROACH TO TECHNOLOGY VALIDATION AND IN-SPACE SYSTEM TECHNOLOGY DEMONSTRATION

ASSUMPTIONS:
- NO LAUNCH VEHICLE CONSTRAINTS
- STS AND SPACE STATION AVAILABLE FOR IN-SPACE TEST BEDS
- SERVICEABILITY IN PLACE
- NASA/DOD NATIONAL TEST BEDS AVAILABLE (NON-INTERFERENCE)

KEY ISSUES:
- HOW DO YOU GET NEW TECHNOLOGY INTRODUCED INTO SYSTEMS WITHOUT INCREASING PROGRAM RISK?

FIGURE 1

SUBSYSTEMS W/G	KEY TECHNOLOGIES
● SPACECRAFT SYSTEM	1. STRUCTURAL CONTROLS INTERACTION
	2. ADVANCED THERMAL CONTROL
	3. ELECTRIC PROPULSION
	4. NUCLEAR POWER SYSTEM
● PROPULSION	1. ADVANCED BIPROPELLANTS
	2. ELECTRIC PROPULSION
	3. FEED SYSTEMS
● ELECTRICAL POWER	1. HIGH VOLTAGE POWER SYSTEMS
	2. DYNAMIC POWER SYSTEMS (SOLAR & NUCLEAR)
	3. HIGH FREQUENCY POWER SYSTEMS
	4. ADVANCED SOLAR ARRAYS
● THERMAL CONTROL	1. ADVANCED HEAT PIPES
	2. ADVANCED FLUID HEAT TRANSFER SYSTEMS
	3. ADVANCED PASSIVE THERMAL CONTROL SYSTEMS

FIGURE 2.

SUBSYSTEMS W/G	KEY TECHNOLOGIES
• TT & C/COMM	1. MICROWAVE COMPONENTS
	2. LOW-COST TEST TECHNIQUES
• DATA MANAGEMENT	1. FAULT TOLERANCE
	2. 10 MOPS SPEED
	3. HIGHER SPEED DATA TRANSMISSION
	4. ON-BOARD DATA STORAGE
• ATTITUDE CONTROL	1. ACS VALIDATION AND TEST
	2. FLEXIBLE STRUCTURE CONTROL
	3. ACS AUTONOMY
	4. LOW NOISE SENSORS AND ACTUATORS
• STRUCTURES & MATERIALS	1. ADVANCED MATERIALS & CHARACTERISTICS
	2. TEST/QUALIFICATION/VERIFICATION METHODS
	3. ZERO-GRAVITY OPERATIONS (ASSEMBLY, PROCESSING, JOINTS/CONNECTORS)
• TELEROBOTICS	1. ZERO-G MANIPULATION
	2. SYSTEM PERFORMANCE VALIDATION
	3. S/C 2000 TEST BED FACILITATOR

FIGURE 3

SPACECRAFT 2000 - TEST BED PHILOSOPHY

GROUND SEGMENT

- INDUSTRY RESOURCES FOR DEVELOPMENT

  EXCEPT

- GOVERNMENT FURNISHED FOR UNIQUE/EXPENSIVE FACILITIES AND INTERFACING/RELATED COMPONENTS IN A STANDARDIZED ENVIRONMENT FOR EVALUATION

SPACE SEGMENT

- TOO COSTLY FOR INDUSTRY
- VALIDATES AVAILABLE TECHNOLOGY (SPACE QUALIFIED)
- ADAPTABLE TEST BED(S) (CONFIGURATION AND LAUNCH VEHICLE INTERFACE)

FIGURE 4

		TEST BEDS					
		GROUND	SPACE				
			STS		SS		FF
SPACECRAFT SYSTEMS	1.	E					X
	2.	E	X	OR	X	OR	X
	3.	E					X
	4.	E & N					X
PROPULSION	1.	E					
	2.	E & N					X
	3.	E	X	OR	X	OR	X
ELECTRIC POWER	1.	E	X	OR	X	AND	X
	2.	E & N			?		X
	3.	E					X
	4.	E	X	OR	X	OR	X
TELEROBOTICS	1.	E	X	OR	X		
	2.	E	X	OR	X		
	3.	E					X
THERMAL CONTROL	1.	E	X	OR	X	OR	X
	2.	E & N			X	OR	X
	3.	E			X	OR	X

FIGURE 5

		TEST BEDS (CONT'D)					
		GROUND	SPACE				
			STS		SS		FF
TT&C/COMMUNICATIONS	1.	E	X	OR	X	OR	X
	2.	E					
DATA MANAGEMENT	1.	E					
	2.	E					
	3.	E					
	4.	E			X	OR	X
ATTITUDE CONTROL	1.	E & N					X
	2.	E & N					X
	3.	E					?
	4.	E					X
STRUCTURES/MATERIALS	1.	E					X
	2.	E & N					X
	3.						

FIGURE 6

SYSTEM DEVELOPMENT

SPACE TEST BED CHARACTERISTICS

- FREE FLYING TEST CAPABILITIES
- CAN BE DECOUPLED FROM SPACE STATION AND STS (OPERATIONALLY AND PROGRAMMATICALLY)
- INSTRUMENTED FOR ENVIRONMENT AND OPERATING PARAMETERS
- RECONFIGURABLE FOR UNIQUE SINGLE AND COMBINATIONS OF SUBSYSTEM TESTING
- RETRIEVABLE/REVISTABLE/SERVICEABLE
- DEVELOPED AND OPERATED BY GOVERNMENT

FIGURE 7

SUMMARY

- NEW HIGHLY LEVERAGED TECHNOLOGY NEEDS BRIDGING SUPPORT
- FLIGHT USE OF TECHNOLOGY REQUIRES ACCEPTABLE RISK
  - GROUND AND SPACE TESTING REQUIRED (FOR USER ACCEPTANCE)
  - (SELECTIVE) FLIGHT QUALIFICATION REQUIRED

FIGURE 8

RECOMMENDED ACTIONS

- OAST TAKE ON NASA ROLE OF FLIGHT VALIDATION OF SPACE SYSTEMS TECHNOLOGY
- OAST ADVOCATE AN INITIATIVE (SPACECRAFT 2000) THAT INCLUDES SPACE TEST CAPABILITY
- OAST EXPLORE INDUSTRY AND INTERAGENCY AGREEMENTS FOR UTILIZATION OF NATIONAL TEST BED CAPABILITIES

FIGURE 9

SYSTEM DEVELOPMENT WORKING GROUP MEMBERSHIP

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R. A. DALEBOUT	GTE SPACENET INC.
D. C. FERGUSON	NASA/LEWIS RESEARCH CENTER
LT. COL. E. JONSON, USAF	AIR FORCE GEOPHYSICS LABORATORY
J. E. LOOS	LOCKHEED MISSILES AND SPACE COMPANY
D. H. MITCHELL	TRW SPACE AND TECHNOLOGY GROUP
M. E. PEREZ-DAVIS	NASA/LEWIS RESEARCH CENTER
D. L. PIVOROTTO	JET PROPULSION LABORATORY
B. RAAB	FAIRCHILD SPACE COMPANY
R. E. REYES	NASA/KENNEDY SPACE CENTER
W. L. SMITH	TRW SPACE AND TECHNOLOGY GROUP

FIGURE 10

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STRUCTURES AND MATERIALS WORKING GROUP REPORT

Robert Torczyner, Chairman
Lockheed Missiles & Space Company, Inc.

Brantley Hanks, Cochairman
NASA Langley Research Center

The Structures and Materials working group addressed a variety of issues relative to the Spacecraft 2000 concept. The objective was to determine key technology areas which the group considered critical to the efficient development of spacecraft of the 21st century.

Based upon the experience of the members of the group and the information presented in the plenary sessions, a brainstorming session brought numerous issues to the attention of the group. These were divided into structures issues and materials issues as presented below:

Structures Issues

- Test bed requirements — ground and flight
- Weight — increase payload mass fraction
- Analytical methods — large flexible structures
- Damping — active and passive
- Joints
- Broad temperature range of operation
- Stringent thermal deformation requirements (low / 0 CTE)
- Test — Large structures — flight and ground (1g)
- Integrated design
- Modularity
- Self adjusting structures
- Cost
- Risk minimization
- Effects of launch loads
- SAMS (Space Assembly, Maintenance and Servicing)

Materials Issues

- Requirements for advanced materials
  - metal matrix, carbon/carbon, and ceramic matrix composites
- Environmental factors — atomic oxygen, radiation, UV
- Contamination
- Analytical capability for material property/performance prediction
- Design data base for advanced materials
- Material standards
- Coatings
- 30 year life
- Extreme thermal cycling

Due to the time constraints of the workshop it was important to limit the issues discussed to a manageable number. Towards that end, the group set some ground rules for selection of key issues. These ground rules are shown in Fig. 1. Although SDI hardware will place exceedingly demanding requirements on structures and materials performance, the SDI specific drivers were not emphasized for the purpose of this workshop. In the materials area, the group focussed primarily on structure, recognizing that all subsystems have materials requirements. For completeness in this discussion, some of these issues are presented below:

- Cryogenic storage — thermal insulation
- Power conversion (800F - 1500F)
- Propulsion (cryogenic - 4000F+)
- Working fluids
- High temperature / high voltage insulation
- Optical materials
- Coatings
- Tribology

The readiness dates referred to in Figure 1 and referenced in following discussions refer to dates when the technology can be available for application to spacecraft. This translates to launch dates approximately five to eight years later.

Fig. 2 lists the technology drivers which were considered to be of prime importance to the evaluation of the current structures and materials state-of-the-art. These drivers reflect structural, environmental, system and cost considerations and resulted in the selection of the four key technology issues which the group then proceeded to further define and evaluate. These issues, presented in Fig. 3 are:

- Advanced materials development
- Analysis / design methods development
- Test of large flexible structures
- Development of diverse structural concepts

Each of the key issues were discussed in detail with the results summarized in Figs. 4 through 7.

Advanced Materials Development (Figs. 4a & 4b)

The basic premise is that 21st Century spacecraft demands will exceed the capabilities of materials currently available and in use. In addition to mechanical and thermomechanical requirements, stringent contamination and environmental resistance requirements will have to be satisfied over a spacecraft lifetime (up to thirty years).

Many of these advanced materials are now being fabricated only in laboratory quantities or for prototype hardware. For these materials to be accepted for S/C 2000 usage, reliable fabrication methods must be developed and implemented.

These will include fabrication on earth and, very possibly, on orbit in some cases.

Materials' properties data bases and standards will be necessary for efficient utilization of advanced materials. This will permit the development of material design allowables with realistic properties, not penalized for lack of data.

The readiness dates presented in Fig. 4b refer to readiness for incorporation into the design phase for S/C 2000. Actual use in flight could be five to eight years later.

Analysis/Design Methods (Figs. 5a & 5b)

A key area of technology concern relates to analysis and design methods for large flexible structures with their complex system interactions. The dynamics and control requirements will necessitate the employment of sophisticated analytical methods to develop these extemely flexible structures. These structures will exhibit non-linear behavior (geometrical, material, joints) which require detailed analysis models for performance predictions. The passive damping characteristics of the structure will have significant impact on its performance and a predictive capability is needed. This includes both material damping and the employment of passive damping mechanisms. The complex interactions with propulsion, thermal control, and other systems will add to the difficulties of the analysis tasks.

In general, joints make up a significant portion of the structural weight of a spacecraft. This can become critical in the case of large structures where the absolute joint weights can become prohibitive. In addition, the joints can have a profound effect on the overall structural stiffness, CTE, and overall dynamics. These complex interactions require new and improved analysis capabilities and design approaches to minimize any negative impacts.

Another area which would benefit advanced spacecraft structures is the design accomodation of material and process variability. By this we mean acceptance of the fact that each part will vary slightly from previous ones and, in order to meet some of the extremely tight overall structural/dimensional/thermomechanical requirements, the designer must learn how to accomodate these variations.

Finally, increased analysis and design capability should lead to cost and time savings (eliminating several iterations in the build-test cycle) and should lead to stuctures with reduced weight and risk.

Testing of Large Flexible Structures (Figs. 6a & 6b)

The third key technology issue addressed by the working group was the requirement to be able to test large flexible structures. We describe these structures as being somewhat like a "wet noodle" in flexibility. They are not self supporting on earth and the 1g environment could be a design load criterion which is inappropriate for the actual structure. The large structures which are envisioned exceed the current facility sizes making new test facilities a requirement on earth and, more importantly, the availability of a space test bed in the near future an important asset to be developed. Testing these structures in space is necessary to verify the analytical techniques used to design them. Vibration modes, damping, load distributions and deformed shapes are all affected by gravity. These and the effects of joint non-linearities should be confirmed through an in-space test capability.

Structural Concepts (Figs. 7a & 7b)

Spacecraft of the 21st Century will employ highly integrated / multi-functional structures. Various logistics drivers such as modularity, standardization, deployability and erectability will impact the design. The concept of space assembly, maintenance and servicing (SAMS) will affect the ultimate structural design. Some of these (integrated / multi-functional) will enhance the structural efficiency of the design while some (modularity, standardization, serviceability) may reduce the structural efficiency while minimizing initial and/or life cycle costs. The key here is to recognize that structures and materials requirements for Spacecraft 2000 will be affected by many new concept drivers which will have to be incorporated into the system.

Summary and Conclusion

As an evaluation of the appropriateness of the selection of these four issues, Fig. 8 presents a cross-check of the issues and their relationship to the technology drivers. As shown in that figure, although all of the issues addressed numerous drivers, the advanced materials development issue impacts six out of the seven drivers and is considered to be the most critical.

Fig. 9 presents a summary of the findings of the Structures and Materials Working Group. The advanced materials technology development and the advanced design/analysis methods development were determined to be enabling technologies with the testing issues and development of new structural concepts considered to be of great importance, although not enabling technologies.

In addition, and of more general interest and criticality, the group established the need for a Government/Industry commitment which does not, at this time, exist. This commitment would call for the establishment of the required infrastructure to facilitate the development of the capabilities highlighted above through the availability of resources and testbed facilities, including a national testbed in space to be in place within ten years.

GROUND RULES

- SDI CONSIDERED, BUT NOT A PRIME DRIVER
- MATERIALS - PRIME EMPHASIS ON STRUCTURE
  - RECOGNIZE ALL SUBSYSTEMS HAVE REQUIREMENTS
- READINESS DATES
  - CURRENT FUNDING
  - SIGNIFICANT FUNDING (ENVIRONMENT OF 1960's)

Figure 1

TECHNOLOGY DRIVERS

- LIGHT WEIGHT
- DIMENSIONAL STABILITY
- PRECISION CONFIGURATION & CONTROL
- LONG LIFE/ENVIRONMENTAL RESISTANCE
- CONTAMINATION CONTROL
- WIDE TEMPERATURE RANGE
- MODULARITY/SAMS

Figure 2

KEY TECHNOLOGY ISSUES

O ADVANCED MATERIALS DEVELOPMENT--
S/C DEMANDS EXCEED CURRENT
MATERIALS' CAPABILITIES

O ANALYSIS/DESIGN METHODS--
LARGE/FLEXIBLE STRUCTURES WITH
SYSTEM INTERACTION

O TEST OF LARGE FLEXIBLE STRUCTURES--
NOT SELF-SUPPORTING IN 1G/TEST METHODS
NON-EXISTENT

O STRUCTURAL CONCEPTS--
LOGISTICS & LIFE CYCLE COSTS

Figure 3

ADVANCED MATERIALS DEVELOPMENT

S/C DEMANDS EXCEED CURRENT MATERIALS CAPABILITIES

MATERIALS PROPERTIES

O SPECIFIC STIFFNESS, STRENGTH, THERMAL/DIMENSIONAL,
LONG-LIFE, NON-CONTAMINATING

O METAL MATRIX (MMC), CERAMIC MATRIX (CMC), CARBON-CARBON (C/C)

RELIABLE MANUFACTURING PROCESSES

O EARTH

O IN-ORBIT

DATA BASE & STANDARDS (STATISTICAL DESIGN ALLOWABLES)

SUPPLIER INFRASTRUCTURE

Figure 4a

ADVANCED MATERIALS [illegible]LOPMENT (CONT'D)

BENEFITS

- O ENABLING TECHNOLOGY
- O INCREASED PAYLOAD FRACTION/PERFORMANCE
- O LIFE/ENVIRONMENT/CONTAMINATION
- O RELIABILITY

READINESS

	CURRENT $	SIGNIFICANT $
MMC	2000	1992
C/C	2005	1997
CMC	2010	1997

Figure 4b

ANALYSIS/DESIGN METHODS

LARGE FLEXIBLE STRUCTURES WITH SYSTEM INTERACTION

- ● DYNAMICS & CONTROL
  - O LARGE STRUCTURES
  - O DAMPING (ACTIVE, PASSIVE)
  - O NON-LINEARITIES (LARGE MOTIONS, JOINTS, MATERIALS)
  - O THERMODYNAMICS
  - O SYSTEM INTERACTION (PROPULSION, THERMAL CONTROL, ENVIRONMENT, ETC.
- ● JOINTS
  - O 50% + OF STRUCTURAL WEIGHT
  - O STIFFNESS, CTE VARIATIONS
  - O MANUFACTURING TOLERANCES
- ● DESIGN ACCOMMODATION OF MATERIAL AND PROCESS VARIABILITY

Figure 5a

ANALYSIS/DESIGN METHODS (CONT'D)

BENEFITS

- O ENABLING TECHNOLOGY FOR LARGE STRUCTURES
- O $ AND TIME SAVINGS (BUILD, TEST ITERATIONS)
- O WEIGHT; INCREASED CONFIDENCE

READINESS*

	CURRENT $	SIGNIFICANT $
DYNAMICS ANALYSIS	1997	1992
JOINTS (GROUND-VALIDATED)	1997	1992

* IF VERIFICATION CAPABILITY FOR LARGE STRUCTURES IN PLACE BY 1990.

Figure 5b

TESTING OF LARGE FLEXIBLE STRUCTURES

GRAVITY EFFECTS

- O NOT SELF-SUPPORTING IN 1G
- O 1G COULD BE DESIGN LOAD CRITERION
- O VIBRATION MODES & DAMPING
- O JOINT NONLINEARITIES
- O DEFORMED SHAPES; INCORRECT LOAD DISTRIBUTIONS

EXCEED FACILITY SIZE

IMPROVED SENSORS

MODULAR ASSEMBLY

Figure 6a

TESTING OF LARGE FLEXIBLE STRUCTURES (CONT'D)

BENEFITS

- VERIFICATION OF ANALYSIS/DESIGN TECHNIQUES
- QUALIFICATION/VERIFICATION METHODS FOR FLIGHT

READINESS

	CURRENT $	SIGNIFICANT $
O GROUND TEST BED	2000	1992
O SPACE TEST BED	2000 +	1997

Figure 6b

STRUCTURAL CONCEPTS

LOGISTICS & LIFE CYCLE COSTS

- HIGHLY INTEGRATED/MULTI-FUNCTIONAL
- MODULAR/EXPANDABLE/STANDARDIZED
- DEPLOYABLE/ERECTABLE/FABRICATABLE
- PRECISION/ADJUSTABLE COMPONENTS
- JOINTS/FITTINGS
- ASSEMBLY/MAINTENANCE/SERVICE

Figure 7a

STRUCTURAL CONCEPTS (CONT'D)

BENEFITS

IMPROVED PAYLOAD FRACTION
MISSION ADAPTABILITY
PERFORMANCE ENHANCEMENT
EFFICIENT PACKAGING/DELIVERY/CONSTRUCTION - WEIGHT / $

READINESS

FUNCTION OF PROGRAM /$/ EXTENT

Figure 7b

TECHNOLOGY ISSUES ADDRESS DRIVERS

	Light Weight	Dimens. Stability	Precision Config. & Control	Long Life & Environmental Resistance	Contam. Control	Wide Temp. Range	Modularity -- SAMS
Advanced Materials Development	X	X	X	X	X	X	
Analysis/Design Mehtods	X		X				X
Test Large/ Flexible Structures	X	X	X				X
Structural Concepts	X	X	X				X

Figure 8

SUMMARY

ENABLING TECHNOLOGIES

- O ADVANCED MATERIALS DEVELOPMENT
- O ADVANCED ANALYSIS/DESIGN METHODS

KEY TECHNOLOGIES

- O TEST OF LARGE FLEXIBLE STRUCTURES
- O DEVELOPMENT OF NEW STRUCTURAL CONCEPTS

GOVERNMENT/INDUSTRY COMMITMENT

- O ESTABLISHMENT OF REQUIRED INFRASTRUCTURE TO FACILITATE DEVELOPMENT OF REQUIRED CAPABILITIES THROUGH AVAILABILITY OF RESOURCES AND TEST BEDS.

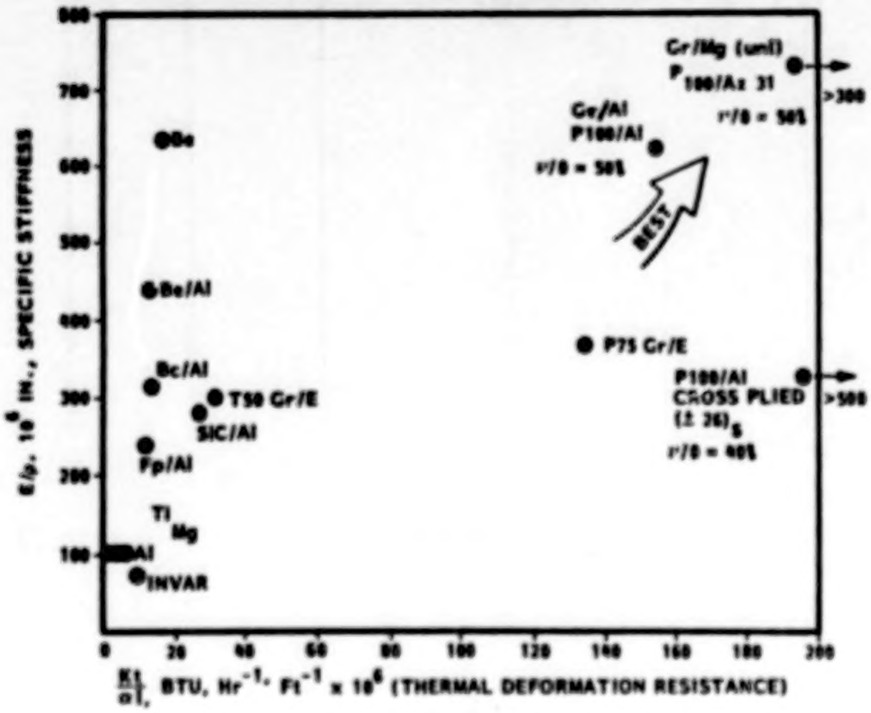
Figure 9

APPENDIX A - DEVELOPMENT OF MATERIALS FOR FUTURE SPACECRAFT

Albert L. Bertram
Naval Surface Weapons Center

FIGURE OF MERIT

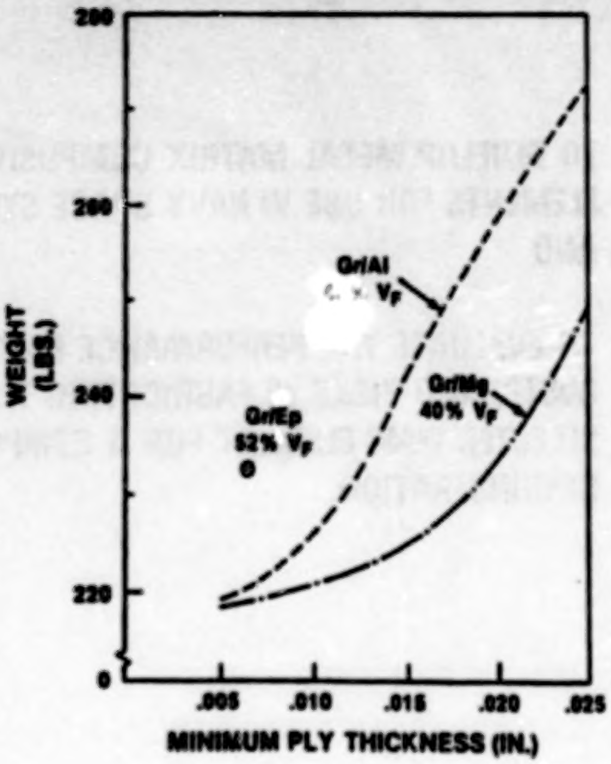
SPECIFIC STIFFNESS VS THERMAL DEFORMATION RESISTANCE



MATERIAL REQUIREMENTS FOR SPACE APPLICATIONS

- LOW DENSITY
- HIGH SPECIFIC STIFFNESS
- ZERO/NEAR ZERO COEFFICIENT OF THERMAL EXPANSION
- DIMENSIONAL STABILITY
- GOOD THERMAL AND ELECTRICAL CONDUCTIVITY
- HIGH TEMPERATURE RESISTANCE
- NO OUTGASSING
- NO MOISTURE ABSORPTION
- RADIATION TOLERANCE
- LASER TOLERANCE

OPTICAL BENCH-TOTAL STRUCTURE WEIGHT VS. MINIMUM PLY THICKNESS



POTENTIAL METHODS FOR FABRICATING THIN-PLY METAL MATRIX COMPOSITES

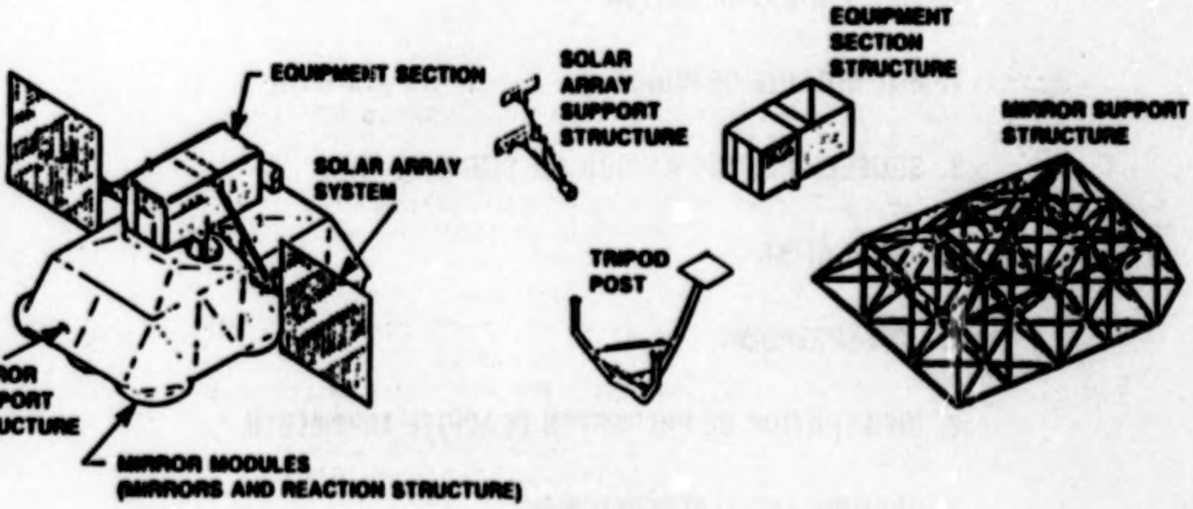
1. THIN WIRE FABRICATION
2. HOT ROLLING OF WIRES
3. SQUEEZE ROLLING AND/OR DIE SIZING OF WIRE
4. ION PLATING
5. TOW-SPREADING
6. INFILTRATION OF PRE-WOVEN GRAPHITE TAPE/CLOTH
7. GROUND AND FLATTENED WIRE

DEVELOPMENT OF METAL MATRIX COMPOSITES FOR UTILIZATION IN SATELLITES

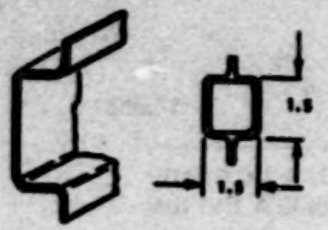
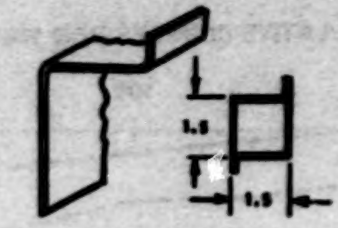
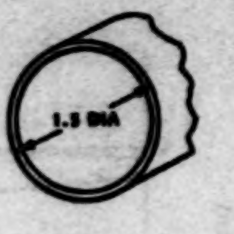
OBJECTIVE: TO DEVELOP METAL MATRIX COMPOSITE ELEMENTS FOR USE IN NAVY SPACE SYSTEMS; AND

TO EVALUATE THE PERFORMANCE PAYOFFS, COSTS, AND RISKS IN FABRICATING THE SELECTED MMC ELEMENT FOR A COMPONENT DEMONSTRATION.

SLCSAT RELAY SATELLITE STRUCTURAL SUBSYSTEM ELEMENTS


EQUIPMENT SECTION
SOLAR ARRAY SYSTEM
MIRROR SUPPORT STRUCTURE
MIRROR MODULES (MIRRORS AND REACTION STRUCTURE)
SOLAR ARRAY SUPPORT STRUCTURE
EQUIPMENT SECTION STRUCTURE
MIRROR SUPPORT STRUCTURE
TRIPOD POST

STRUCTURAL ELEMENTS FOR TESTING

		
BASIC ELEMENT: DIFFUSION-BONDED HAT SECTION CREEP FORMED **TUBE:** TWO HAT SECTIONS ARE WELD-BONDED INTO RECTANGULAR TUBE **MATERIAL:** Gr/Mg or Gr/Al, 2 PLY, UNIDIRECTIONAL, V_f = 45%, t = .05 in. **DEVELOPMENT REQUIRED:** • CREEP FORMING PARAMETERS • SMALL BEND RADII • WELD-BONDING PARAMETERS **NUMBER** 10 x 12 IN. LONG MAKES 5-□-TEST ELEMENTS	**BASIC ELEMENT:** MODIFIED Z-SECTION DIFFUSION-BONDED IN MATCHED DIES **TUBE:** TWO Z-SECTIONS ARE WELD-BONDED INTO RECTANGULAR TUBE **MATERIAL:** Gr/Mg OR Gr/Al 2 PLY, UNIDIRECTIONAL, V_f = 45%, t = .05 in. **DEVELOPMENT REQUIRED** • LARGE MATCHED DIES • LENGTH TO 60 IN. • Gr/Mg PARAMETERS **NUMBER** 10Z x 12 IN LONG MAKES 5 □ TEST ELEMENTS	**BASIC ELEMENT** ROUND TUBE 2 PLY PULTRUDED WITH SURFACE FOILS **MATERIAL:** Gr/Mg OR Gr/Al UNIDIRECTIONAL t = .05, VF 45% **DEVELOPMENT REQUIRED** • LENGTH TO 60 in. • Gr/Mg PARAMENTERS • VOLUME FRACTION > 45% • STRAIGHTNESS **NUMBER** 5 PCS X 10 in. LONG

INERTIAL MEASUREMENT UNIT — STABLE MEMBER

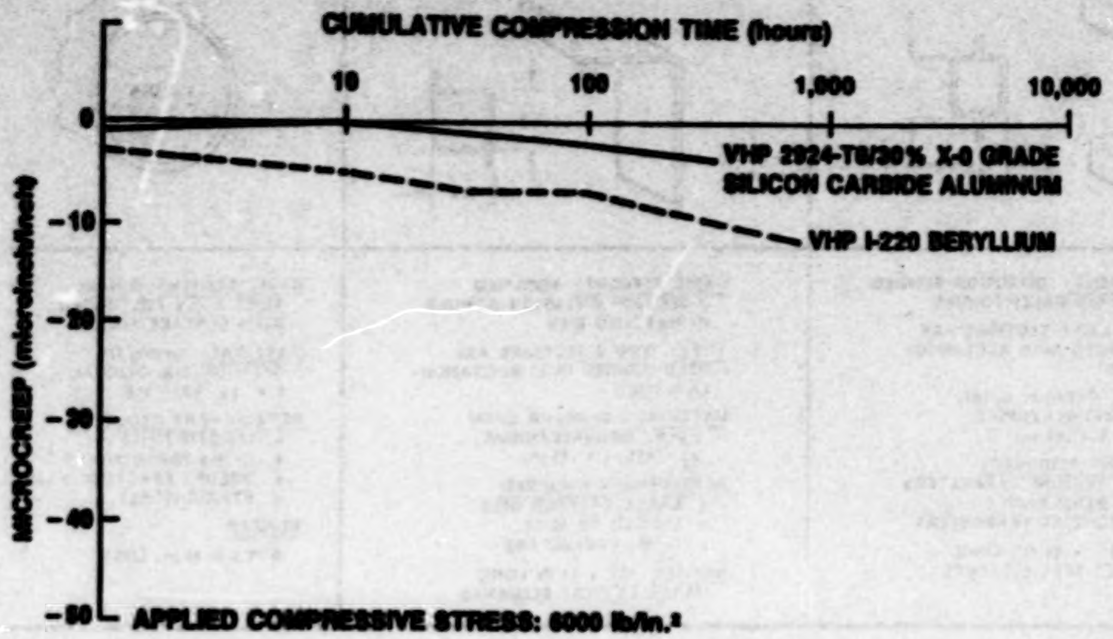
OBJECTIVE: DEVELOP A MATERIAL TO REPLACE BERYLLIUM FOR OPTICAL BENCH APPLICATIONS (SHIPS, TACTICAL MISSILES, STRATEGIC MISSILES)

RATIONALE FOR DEVELOPMENT:

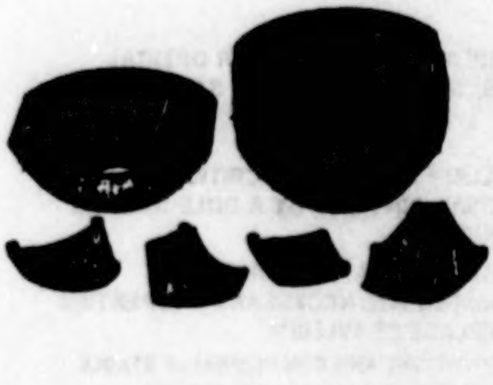
- BERYLLIUM IS A COSTLY CRITICAL MATERIAL, SUPPLIED BY A SOLE SOURCE PRODUCER
- SiC/Al METAL MATRIX COMPOSITE POSSESSES THE NECESSARY PROPERTIES TO REPLACE BERYLLIUM:
  - LIGHTWEIGHT AND DIMENSIONALLY STABLE
  - ISOTROPIC MECHANICAL PROPERTIES
  - THERMAL EXPANSION AND THERMAL CONDUCTIVITY TAILORABLE TO MATCH BERYLLIUM

IMU STABLE MEMBER

MICROCREEP CHARACTERISTICS UNDER MAXIMUM LOAD



MACHINED MMC GUIDANCE SYSTEM COMPONENTS



ELECTRONICS SHELL, INSTRUMENT COVERS AND STABLE MEMBER

ASSEMBLY OF COMPONENTS

DATA SUMMARY FOR P-2056

40 v/o B_4C/Mg – 6 Zn

(7" DIA X 1-5/8" THICK, AS-PRESSED; FORGED TO 1-5/16" THICK)

AS-PRESSED DENSITY: 100% OF THEORETICAL

CONDITION	TEST NO.	E, msi	UTS, ksi	YS, ksi	PL, ksi	ε_f%
AS-FORGED	7669	18.3	40.3	–	23.0	.206
	7670	17.8	36.3	–	22.3	.231
	7683	17.6	23.4	–	–	.135
	7684	17.6	35.5	–	22.3	.222

E= YOUNG'S MODULUS

UTS= ULTIMATE TENSILE STRENGTH

YS= YIELD STRENGTH, .2% OFFSET

PL= PROPORTIONAL LIMIT

ε_f= STRAIN TO FRACTURE

BORON CARBIDE REINFORCED MAGNESIUM COMPOSITE DEVELOPMENT (IN-HOUSE EFFORT)

OBJECTIVE:

MICROSTRUCTURAL EXAMINATION AND MECHANICAL PROPERTY DETERMINATION OF B_4C/Mg COMPOSITES FOR SPACE APPLICATIONS SUCH AS END FITTINGS, CONNECTORS, BRACKETS, OR SPACERS.

REQUIREMENTS:

LIGHTWEIGHT, HIGH SPECIFIC STIFFNESS, LOW CTE, ISOTROPIC PROPERTIES

APPROACH:

THE EFFECT OF MATRIX (ZK60A, AZ91C), FORM (BILLET, EXTRUSION, FORGING), AND VOLUME PERCENT REINFORCEMENT (40V/0) WILL BE EVALUATED BY MICROSTRUCTURAL EXAMINATION, TENSILE TESTING, CTE DETERMINATION, AND CORROSION TESTING.

BORON CARBIDE REINFORCED MAGNESIUM COMPOSITE DEVELOPMENT
(CONTRACTOR EFFORT)

OBJECTIVE:

TO DEVELOP B_4C/Mg FOR THE GIMBAL APPLICATION IN NEXT GENERATION TRIDENT II INERTIAL MEASUREMENT UNIT COMPONENTS.

REQUIREMENTS:

LOW DENSITY, DIMENSIONAL STABILITY, HIGH SPECIFIC STIFFNESS

APPROACH:

A 35 V/0 B_4C/ZK60A - Mg COMPOSITE WILL BE DEVELOPED AND EVALUATED FOR:

> MICROCREEP RATE, MICROYIELD STRENGTH, CTE, THERMAL CONDUCTIVITY, DENSITY, YIELD STRENGTH, ULTIMATE TENSILE STRENGTH, YOUNG'S MODULUS, ELONGATION, MACHINING STUDIES, CORROSION STUDIES

CARBON–CARBON

CARBON-CARBON FOR SPACE STRUCTURES

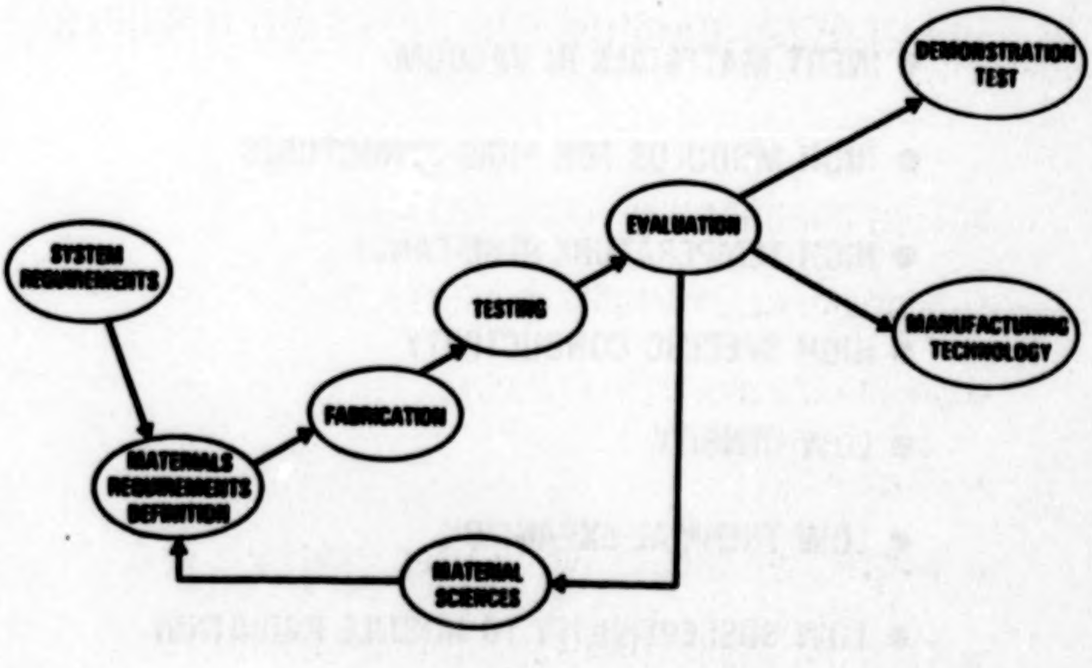
- HIGH CONDUCTIVITY RADIATOR PANELS
- DIMENSIONALLY STABLE STRUCTURES
- HARDENED SPACECRAFT SHELLS
- HEAT PIPES
- PROTECTIVE SHIELDS AND SENSOR COVERS
- THERMAL INSULATION FOR CRITICAL COMPONENTS

MATERIALS TECHNOLOGY NEEDS

- FINE DIAMETER FIBERS
- VERY HIGH MODULUS FIBERS
- THIN PANEL TECHNOLOGY
- THIN-WALLED TUBES
- ATTACHMENT AND JOINING
- TEST METHODS
- DESIGN DATA BASE
- MANUFACTURING TECHNOLOGY

CARBON–CARBON COMPOSITE TECHNOLOGY PROGRAM:

TECHNICAL APPROACH



SYSTEM REQUIREMENTS

MATERIALS REQUIREMENTS DEFINITION

FABRICATION

TESTING

EVALUATION

DEMONSTRATION TEST

MANUFACTURING TECHNOLOGY

MATERIAL SCIENCES

CARBON–CARBON FOR SPACE STRUCTURES

CURRENT AND NEAR TERM PLANS:

MATERIALS REQUIREMENTS DEFINITION - ASSESS NEAR TERM SYSTEMS NEEDS AND IDENTIFY CRITICAL MATERIAL PROPERTIES THAT HAVE TO BE DEVELOPED AND DEMONSTRATED

MATERIAL FABRICATION - DESIGN AND FABRICATION CRITICAL MATERIALS FOR EARLY EVALUATION. CRITICAL MATERIALS TECHNOLOGY IDENTIFIED BRAIDED TUBES (10 TO 15 MILS WALL THICKNESS).

THERMAL/MECHANICAL CHARACTERIZATION - DEFINE TEST MATRICES FOR TESTING OF THIN WALLED CARBON-CARBON COMPOSITES. EMPHASIS IS PLACED ON MEASURING MODULUS, EXPANSION AND CONDUCTIVITY. SPECIAL TEST PROCEDURES WILL BE DEVELOPED.

CONCEPT DEMONSTRATION - FULL SIZE PANELS AND TUBES WILL BE FABRICATED TO DEMONSTRATE MANUFACTURING TECHNOLOGY. THERMAL CYCLE TESTS WILL BE CONDUCTED ALONG WITH CONTINUOUS AND PULSED LASER TESTS.

MATERIALS REQUIREMENTS DEFINITION

- INERT MATERIALS IN VACUUM
- HIGH MODULUS FOR RIGID STRUCTURES
- HIGH TEMPERATURE RESISTANCE
- HIGH SPECIFIC CONDUCTIVITY
- LOW DENSITY
- LOW THERMAL EXPANSION
- LOW SUSCEPTIBILITY TO HOSTILE RADIATION

N8
10095

N88-10095

THERMAL CONTROL WORKING GROUP REPORT

Robert Haslett, Chairman
Grumman Aerospace Corporation

E. Thomas Mahefkey, Cochairman
USAF Wright Patterson Air Force Base

The Thermal Control Working Group limited its evaluation to issues associated with earth orbiting and planetary spacecraft with power levels up to 50 kW (Fig. 2). Other missions were judged to be receiving sufficient emphasis (e.g., Space Station, weapon platforms) or were too unique from a thermal design standpoint (e.g., solar probes) for consideration of generic technology needs.

A spacecraft ultimately must reject, as waste heat, all on-board electrical power. The importance of thermal control in spacecraft design has, therefore, increased dramatically in the last few years commensurate with growth in power levels. NASA, Air Force, DOE and SDIO all have numerous thermal technology programs underway (Fig. 3). The working group reviewed these on-going programs against the postulated Spacecraft 2000 missions and design challenges (Fig. 4) to identify new system requirements.

The Group's conclusion was that new technology was necessary to cope with future high watt density electronics, high temperature heat transport and rejection, long term storage of cryogenics and the emerging need to harden all military spacecraft against a wide variety of threats (Fig. 5).

An integrated thermal system for any particular Spacecraft 2000 application will be comprised of many different elements; a list of some of the options the thermal designer has at his disposal are shown on Fig. 6. The number of elements involved prompted a discussion of the value of standardization to increase reliability and lower costs (Fig. 7). The group's consensus was that large weight penalties can result if thermal systems are not uniquely matched to the spacecraft. Hardware standardization in the near term was, therefore, not judged to be cost effective since launch costs dominate. As low cost-to-orbit heavy lift launch vehicles become available this conclusion would change. The one hardware area where standardization would have immediate benefits is in interface designs (e.g., fluid disconnects) to allow orbital replaceable units (ORU's) to be provided by various suppliers (including foreign participants in international programs). Another area of standardization that should be pursued under the S/C 2000 initiative is specifications and test methods for the qualification of new system elements.

The Working Group also concluded that particular emphasis should be placed on the application of robotics to the on-orbit assembly, reconfiguration and maintenance of S/C 2000 thermal systems (Fig. 8).

The primary output of the working group discussions was the definition of high payoff thermal technologies required to meet the objectives of S/C 2000 (Fig. 9). These nine (9) initiatives form the long range technology development plan recommended for implementation. Each of these key thermal system design drivers was assessed by first identifying the problem, the development objective, the approach to achieve possible solutions and any special facilities and equipment that would be needed to meet the development objectives. These nine individual technology plans are presented in Figs. 10 to 18.

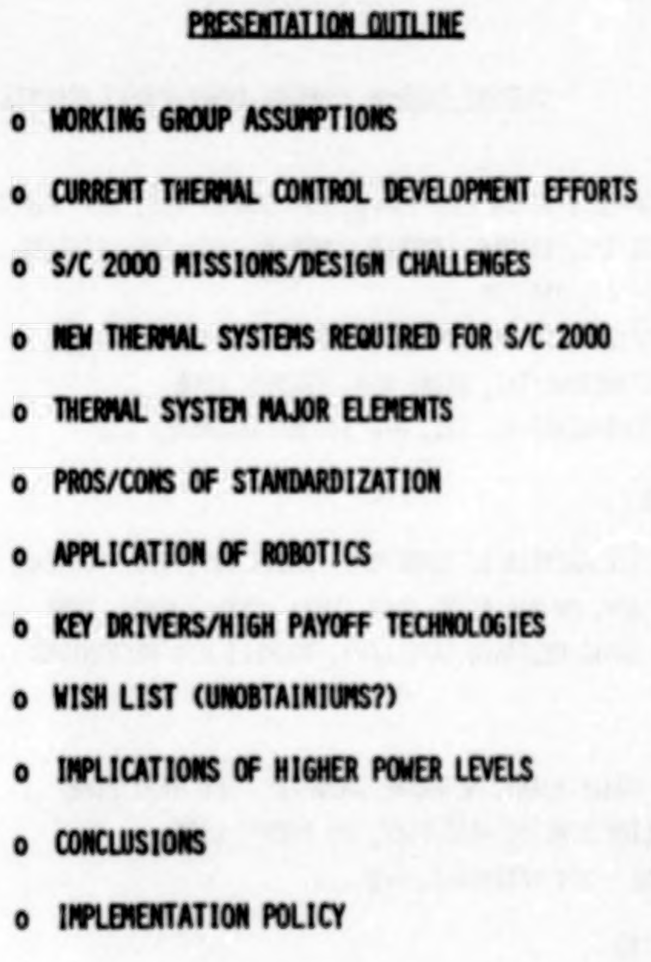
These nine key technologies were deemed essential and also met the constraint of appearing feasible within the S/C 2000 time frame. An additional high payoff "wish list" was also prepared to challenge the "inventors" in the thermal community.

As stated earlier, the majority of the group's deliberations were directed at spacecraft type power levels ($<$ 50 kW). Weapon platforms, nuclear propelled manned planetary misions, etc., could require much higher power levels (megawatts). The heat rejection radiator dominates the design of these systems, so development implications (Fig. 20) are to seek very innovative lightweight radiator concepts, efficient heat exchangers to minimize system temperature drops and high temperature (liquid metal) systems to maximize rejection temperature.

In conclusion (Fig. 21), the group determined that the unique new heat pipe radiator and two-phase heat transport systems being developed for Space Station are necessary precursors, but do not meet different S/C 2000 requirements including long life without manned maintenance capability, high watt density electronics, long term cryogenic storage for sensors and/or propulsion/power and threat survivability for military spacecraft. The S/C 2000 initiative should, therefore, include the necessary basic/applied research and ground/space testing to achieve the essential nine (9) new technologies.

Recommended implementation steps (Fig. 22) include the establishment of a steering committee to coordinate the diverse government and industry thermal system development programs to exchange information and avoid overlap. The most pressing need is in-orbit research and development since two-phase thermal systems are inherently not completely ground testable. A space program analogous to the very successful X aircraft series is clearly called for. Of lesser importance, but worth mentioning, are recommendations that the government reexamine the roles of Universities, National Labs and Industry to confirm that their different expertise is being used to the best advantage. There was some concern expressed by the group that there has been a gradual blurring of roles with all segments of the U.S. technical community competing for the same work with resultant duplication and waste of resources. Finally, there was a similar observation that there may be redundancy in test facilities. It was suggested that an up-to-date handbook of government, university and industry thermal test facilities be prepared. One objective would be to determine if selected national test facilities are desirable (analogous to the national wind tunnels operated by NASA and the Air Force for aircraft development).

It was recognized that the programmatics of X series spacecraft and national test beds is a difficult problem (e.g., cost sharing, protecting proprietary rights, etc.) but the approach has been successfully applied to aircraft development for many years.



PRESENTATION OUTLINE

- WORKING GROUP ASSUMPTIONS
- CURRENT THERMAL CONTROL DEVELOPMENT EFFORTS
- S/C 2000 MISSIONS/DESIGN CHALLENGES
- NEW THERMAL SYSTEMS REQUIRED FOR S/C 2000
- THERMAL SYSTEM MAJOR ELEMENTS
- PROS/CONS OF STANDARDIZATION
- APPLICATION OF ROBOTICS
- KEY DRIVERS/HIGH PAYOFF TECHNOLOGIES
- WISH LIST (UNOBTAINIUMS?)
- IMPLICATIONS OF HIGHER POWER LEVELS
- CONCLUSIONS
- IMPLEMENTATION POLICY

Figure 1.

WORKING GROUP ASSUMPTIONS

- WILL CONSIDER
  - SCIENTIFIC, COMMERCIAL & MILITARY SPACECRAFT
  - SURVIVABILITY TO NATURAL & MILITARY THREATS
  - OTV'S; CHEMICAL & ELECTRIC PROPULSION, EXPENDABLE & REUSEABLE
  - ON ORBIT DEPLOYMENT/ASSEMBLY, MAINTENANCE
  - POWER LEVELS UP TO 50 KW
- WILL NOT CONSIDER
  - WEAPON PLATFORMS
  - MANNED SPACECRAFT
  - LAUNCH VEHICLES
  - NEAR SOLAR PROBES

Figure 2.

CURRENT THERMAL CONTROL DEVELOPMENT EFFORTS

o **NASA**

LeRC - SPACE STATION T/M, $2\phi\mu g$, H-T COMPOSITES, HEAT PIPES, LDR ...
JSC - STS T/C, THERMAL TESTBED, THERMAL VAC, ENV. TESTING ...
JPL - SP-100, RTG T/M ...
GSPC - SCIENTIFIC INSTRUMENT, OPTICS, PRECISION T/C, CPL ...
LaRC - STRUCTURE T/C, DCHX, H.P. LEADING EDGE ...
MSFC - REFRIGERATORS, TES, 0-G T/C MAINTAINENCE ...

o **AIRFORCE**

AFWAL - T/C MATERIALS, TRANSPORT, RADIATORS, TES, COOLERS, SURVIVABILITY ...
AFRPL - ADV. MW RADIATORS (LDR, MBR), CRYOSTORAGE, DCHX ...
AFOSR - BASIC RESEARCH CAPILLARY, DROPLET H/X MECHANISMS ...

o **DOE**

"MMW" - CURIE POINT, MEMBRANE RADIATOR, EFD HEAT PIPES ...
LANL - LIQUID METAL HEAT PIPE, EM PUMPS, LIFE
ORNL, ANL - H-T MATERIALS, TES ...

o **SDIO** - TBD ......

Figure 3.

S/C 2000 MISSION AREAS & DESIGN CHALLENGES

- MISSION AREAS
  - LWIR, OPTICAL EARTH RESOURCES ...
  - COMMUNICATION PLATFORMS ...
  - SPACE MANUFACTURING ...
  - OTV ...
  - RADAR ATC ...
- DESIGN CHALLENGES
  - 10 - 30 YEAR DESIGN LIFE ...
  - LEO ASSEMBLY, LEO/GEO TRANSFER ...
  - RESUPPLY, MAINTAINENCE ...
  - INCREASED P/L MASS FRACTION ...
  - GROWTH, MODULARITY, STANDARDIZATION ... AFFORDABILITY ...
  - INCREASED IN-SPACE DATA PROCESSING ...
  - COMPACT, LOCALLY SHIELDED ELECTRONICS ...
  - INTEGRABILITY, TESTABILITY ...

Figure 4.

NEW THERMAL SYSTEMS REQUIRED FOR S/C 2000

- VERY HIGH HEAT FLUX REMOVAL FORM DENSE ELECTRONICS ("CRAY IN SPACE")
- NEW HIGH TEMP COOLING SYSTEMS
  - NaS AND LITHIUM BATTERIES (350 - 500°C)
  - HIGH TEMP SOLID STATE ELECTRONICS (150 - 250°C)
- HIGH TEMP RADIATORS & THERMAL STORAGE FOR ADVANCED POWER SYSTEMS
  - DIPS
  - NUCLEAR
  - ADVANCED SOLAR DYNAMIC
- LONG TEMP CRYO STORAGE (REFRIGERATORS/RADIATORS)
- LASER, NUCLEAR RADIATION ETC RESISTENT MATERIALS FOR THREAT SURVIVABILITY

Figure 5.

THERMAL SYSTEM MAJOR ELEMENTS

COATINGS
INSULATION/THERMAL ISOLATORS
HEATERS/CONTROLLERS
RADIATORS (FLUID LOOP & HEAT PIPE)
HEATTRANSPORT LOOPS (SINGLE & TWO PHASE)
THERMAL STORAGE
ROTATING JOINTS
HEAT EXCHANGERS
HEAT PUMPS
REFRIGERATORS

DISCONNECTS
FLEX COUPLINGS
LOUVERS/SHADE'S
HEAT PIPES
STORED CRYOGENS
MECHANISMS FOR DEPLOYMENT/ASSEMBLY
PLUME SHIELDS
THERMOELECTRIC COOLERS
CONTACT INTERFACE MATERIALS
THERMAL SWITCHES/DIODES

Figure 6.

PROS/CONS OF STANDARDIZATION

- STANDARDIZATION COULD SAVE HARDWARE COST BUT PENALIZES MASS/VOLUME
- LAUNCH COST IS CURRENTLY MAJOR COST ELEMENT

CONCLUSION: HARDWARE STANDARDIZATION IN NEAR TERM NOT COST EFFECTIVE

- STANDARDIZATION OF SPECS, TEST METHODS ETC.COULD PROVIDE COST BENEFITS
- STANDARDIZATION OF INTERFACES IS NECESSARY FOR ORU'S

Figure 7.

APPLICATION OF ROBOTICS

- MAKE FLUID CONNECTIONS
- BOLT ELECTRONICS TO COLD PLATES
- ASSEMBLE RADIATORS
- REPAIR LEAKS
- REMOVE & REPLACE COMPONENTS (PUMPS, VALVES ETC.)
- REPLACE FAILED INSTRUMENTATION
- REPLENISH FLUIDS
- CLEAN CONTAMINATED THERMAL COATINGS, OPTICS ETC.

Figure 8.

KEY DRIVERS/HIGH PAYOFF TECHNOLOGIES

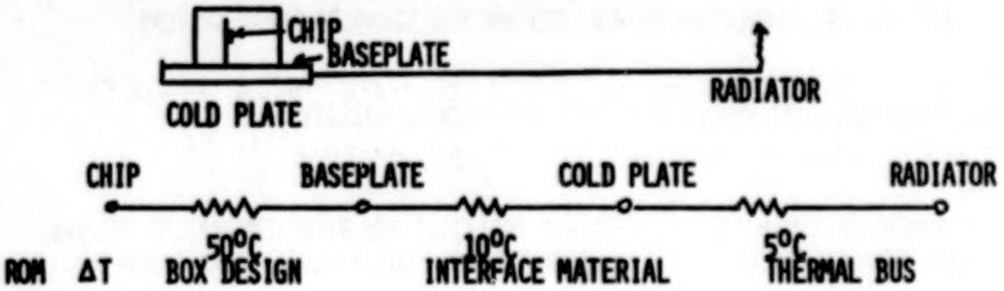
- o BOX LEVEL THERMAL CONTROL
- o HIGH TEMP COOLING LOOPS/ RADIATORS (150 - 500°C)
- o RADIATORS/THERMAL STORAGE FOR ADVANCED POWER SYSTEMS (TO 700°C)
- o LONG TERM CRYO STORAGE
- o THREAT HARDENED MATERIALS
- o BASIC/APPLIED RESEARCH ON LONG LIFE FLUIDS/MATERIALS COMPATIBILITY
- o SCALING/SIMULATION
- o TWO PHASE HEAT TRANSFER MODELLING
- o LONG LIFE ROTATING FLUID GIMBAL

Figure 9.

KEY DRIVER: BOX LEVEL THERMAL CONTROL

PROBLEM

- o S/C LEVEL THERMAL CONTROL SYSTEM BASIC OBJECTIVE IS TO MAINTAIN COMPONENT (SWITCH, DIODE) ALLOWABLE TEMPERATURE.
- o RADIATOR SIZED RECOGNIZING COMPONENT TO RADIATOR ΔT



OBJECTIVE

- o REDUCE RADIATOR SIZE (COST, WEIGHT, DRAG). NOW DRIVEN BY HIGH ΔT'S AT BOARD AND BASEPLATE. POTENTIAL FOR 50% RADIATOR SIZE REDUCTION.

APPROACH

- o INSTITUE COMPONENT THERMAL DESIGN EFFORT
  - -UTILIZE BOARD MINI-HEAT PIPES (OR BOARD INTEGRAL WICKS)
  - -IMPROVE BASEPLATE/COLD PLATE INTERFACE CONDUCTANCE OR ELIMINATE USING INTEGRAL DISCONNECTABLE FLUID PATH.

SPECIAL FACILITIES AND EQUIPMENT

NONE

Figure 10.

KEY DRIVER: HIGH TEMPERATURE COOLING LOOPS/RADIATORS

PROBLEM

- o EXTEND HEAT PIPE TECHNOLOGY TO NEW HIGHER OPERATING TEMPERATURE AND APPLICATION REGIMES

OBJECTIVE

- o DEVELOP THE TECHNOLOGY BASE FOR THERMAL CONTROL OF HIGH TEMPERATURE POWER ELECTRONICS (150°C - 200°C) AND ADVANCED NaS AND Li BATTERIES (350 - 500°C), SOLARDYNAMIC AND REACTOR P/S SPIN OFF APPLICABILITY ...

APPROACH

- o MATERIAL SELECTION - CLADS, WORKING FLUIDS, PROCESSING TECHNIQUES, MATERIALS COMPATIBILITY, LIFE TEST DATA BASE ...
- o TRANSPORT DESIGN
  - LOAD INTERFACE HEAT EXCHANGE DESIGN (OPERATING T, HEAT FLUXES, ΔT) ...
  - HEAT TRANSPORT (LOAD TO RADIATOR) ...
  - RADIATOR - VCHP DEV, HP/FIN THERMO-MECHANICAL INTERFACE ...
  - UTILIZE POTASSIUM, MERCURY, CESIUM/TITANIUM OR COMPOSITE HEAT PIPE OR E/M PUMP ASSISTED NaK HEAT PIPE ... COMPOSITE RADIATOR FIN (HIGH K/ρ)

SPECIAL FACILITIES EQUIPMENT

- LIQUID METAL HANDLING, PROCESSING EQUIPMENT...
- HI VAC LIFE TEST FACILITIES ...
- PRE/POST TEST COMPATIBILITY DIAGONISTICS ...METALLURGICAL

Figure 11.

KEY DRIVER: RADIATOR/THERMAL STORAGE FOR ADVANCED POWER SYSTEMS

PROBLEM

- o HIGH POWER MISSIONS EXCEED NEAR-TERM RADIATOR CAPABILITY

OBJECTIVE

- o DEVELOPMENT OF ADVANCED, LIGHT WEIGHT RADIATORS AND HIGH TEMPERATURE THERMAL STORAGE DEVICES DESIGNED TO HANDLE HEAT LOADS FROM NUCLEAR/SOLAR POWER SYSTEMS.

APPROACH

- o IDENTIFY HEAT REJECTION REQUIRMENTS FOR SOLAR/NUCLEAR POWER SYSTEMS
- o DEVELOP ENABLING CONCEPTS TO MEET REQUIREMENTS:
  - THERMAL STORAGE INCORPORATING MOLTEN SALT
  - ENCAPSULATED TES
  - COMPOSITE MATERIAL, LIQUID METAL HEAT PIPE RADIATORS
  - HIGH EFFICIENCY HEAT EXCHANGERS
  - REFRACTORY MATERIALS

SPECIAL FACILITIES EQUIPMENT

- o SPACE SIMULATION CHAMBERS WITH HAZARDOUS MATERIALS HANDLING

Figure 12.

KEY DRIVER: LONG TERM CRYOGENIC STORAGE

PROBLEM

- o BOILOFF LOSS IS A SEVERE WEIGHT PENALTY FOR SPACECRAFT

OBJECTIVE

- o DEVELOP LONG TERM CRYOGENIC STORAGE TECHNOLOGY TO STORE HELIUM, HYDROGEN & OXYGEN UP TO 10 YEARS.

APPROACH

- o DEVELOP: HIGH PERFORMANCE INSULATIONS, VAPOR COOLED SHIELD, LOW HEAT LEAK SUPPORTS & PLUMBING, AND CRYO REFRIGERATORS.
- o BUILD & TEST LONG TERM CRYOGENIC STORAGE SYSTEM
- o DEMONSTRATE ON GROUND & ON ORBIT.

SPECIAL FACILITIES

- o HAZARDOUS THERMAL VACUUM FACILITY

NOTE: TECHNOLOGY DEVELOPMENT CURRENTLY UNDERWAY NEEDS CONTINUED SUPPORT REQUIRED)

Figure 13.

KEY DRIVER: THREAT HARDENED MATERIALS

PROBLEM

- o THERMAL CONTROL COMPONENT AND SURFACES MAY BE SUBJECTED TO SEVERE HOSTILE ENVIRONMENTS. REQUIREMENTS INCLUDE COATINGS WITH SELECTIVE WAVELENGTH DEPENDENT PROPERTIES, RADIATION INSENSITIVE COATINGS AND FLUIDS, BLAST AND MECHANICAL IMPACT SURVIVABLE COMPONENTS, AND DESIGNS/COMPONENTS TO ACCOMMODATE PULSED LOADS.

OBJECTIVE

- o DEVELOP ADVANCED THERMAL CONTROL MATERIALS, COMPONENTS, CONSTRUCTIONS AND CONFIGURATIONS CAPABLE OF WITHSTANDING PROJECTED THREATS

APPROACH

- o (1) GENERAL DESIGN CONCEPTS FOR DIFFERENT OPERATIONAL REGIMES
- o (2) CONDUCT TRADES
- o (3) SELECT PREFERRED CONCEPTS
- o (4) FABRICATE AND TEST

SPECIAL FACILITIES AND EQUIPMENT

- o OPTICAL PROPERTIES MEASUREMENT, HIGH HEATING, RADIATION, AND HIGH SPEED MECHANICAL IMPACT EQUIPMENT
- o THERMAL VACUUM TEST VERIFICATION

Figure 14.

KEY DRIVER: BASIC/APPLIED RESEARCH IN LONG LIFE FLUIDS/MATERIALS COMPATIBILITY

PROBLEM

- o EXTEND CURRENT HEAT PIPE AND CAPILLARY LOOP COMPATIBILITY DATA BASE TO 10 YEARS (+) FOR 300K - 1000K TEMPERATURE OPERATING REGIME

OBJECTIVE

- o CHARACTERIZE THE LIFE AND PERFORMANCE STABILITY OF ADVANCED TWO PHASE HEAT TRANSFER DEVICES IN 300K-1000K REGIME

APPROACH

- o CHARACTERIZE CORROSION, MASS TRANSPORT, AND PERFORMANCE DEGRADATION MECHANISMS IN ADVANCED 2 PHASE TRANSPORT DEVICES AS FUNCTION OF NORMALIZED MASS FLOW RATES, TEMPERATURE, VAPOR PRESSURE, VACUUM BACKGROUND PRESSURE
- o CHARACTERIZE OPTIMUM PROCESSING, ASSEMBLY, FABRICATION TECHNIQUES TO ENHANCE ATTAINABLE LIFE
- o CONDUCT ACCELERATED AND REAL TIME LIFE TESTS TO VERIFY CORROSION MODEL VALIDITY.

SPECIAL FACILITIES AND EQUIPMENT

- o HIGH VACUUM TEST FACILITIES
- o SURFACE CHEMISTRY, METALLURGICAL DIAGONISTICS
- o LIQUID METAL HANDLING AND ASSAY EQUIPMENT

Figure 15.

KEY DRIVER: SCALING/SIMULATION

PROBLEM

- o TESTING OF FULL SIZE FLIGHT HARDWARE OFTEN DIFFICULT OR IMPOSSIBLE DUE TO SIZE
- o MICRO - G OPERATION UNVERIFIABLE PRIOR TO FLIGHT

OBJECTIVE

- o PREDICT IN-FLIGHT PERFORMANCE BY MEANS OF GROUND TEST

APPROACH

- o REDUCED SCALE 1-G AND/OR BRIEF MICRO-G TESTING
- o DEVELOP ANALYTICAL TECHNIQUES TO EXTRAPOLATE REDUCED SCALE TEST DATA TO THE FULL SIZE CONFIGURATION AND 1-G (OR BRIEF MICRO G) ENVIRONMENT TO PROTRACTED MICRO-G OPERATION.

SPECIAL FACILITIES AND EQUIPMENT

- o EXISTING

Figure 16.

KEY DRIVER: TWO PHASE HEAT TRANSFER MODELLING

PROBLEM

- TWO PHASE HEAT TRANSFER ANALYTICAL TOOLS NEEDED TO PREDICT SYSTEM PERFORMANCE

OBJECTIVE

- DEVELOP SOFTWARE TO PERMIT CONFIDENT PREDICTIONS OF PERFORMANCE

APPROACH

- CONSTRUCT COMPUTER PROGRAM WITH TRANSIENT AND STEADY STATE CAPABILITY AND GENERAL APPLICABILITY - VARIABLE G, ARBITRARY DIMENSIONS, SELECTED WORKING FLUID AND MATERIALS
- CORRELATE AGAINST DATA FROM VARIOUS TEST CONFIGURATIONS
- USE VALIDATED MODEL TO CHARACTERIZE IN-FLIGHT PERFORMANCE

Figure 17.

KEY DRIVER: LONG LIFE ROTATING FLUID GIMBAL

PROBLEM

- MANY MILITARY & SCIENCE MISSIONS REQUIRE TAKING COOLING LINES ACROSS GIMBALS.
- SPACE STATION IS DEVELOPING A ROOM TEMPERATURE GIMBAL
- PERIODIC MAINTENANCE IS PERMITTED

OBJECTIVE

- DEVELOP LONG LIFE CRYOGENIC AND HIGH TEMP ROTATING FLUID GIMBALS

APPROACH

- PHASED PROGRAM
  - -LONG LIFE SEAL TESTS
  - -GIMBAL DESIGN AND PROTOTYPE FAB. (CRYO & HIGH TEMP)
  - -LIFE TESTS

SPECIAL FACILITIES AND EQUIPMENT

- STD VACUUM CHAMBER

Figure 18.

WISH LIST (UNOBTAINIUMS?)

- CRYOGENIC THERMO ELECTRICS (HIGH COP AT LARGE ΔT),OR OTHER TYPE OF NO-MOVING-PARTS REFRIGERATOR
- INTERFACE MATERIAL WITH CONDUCTANCE OF BRAZED JOINTS
- PHOTOCHROMIC COATINGS THAT CHANGE α & ϵ WITH TEMPERATURE (PASSIVE LOUVER)
- HEAT PIPE FLUID FOR APPLICATION BETWEEN WATER AND LIQUID METALS
- HIGH THERMAL ENERGY STORAGE SYSTEMS
- EXTREMELY HIGH CONDUCTIVITY HIGH TEMP. RADIATOR FINS (BETTER THAN CARBON/CARBON)

Figure 19.

IMPLICATIONS OF HIGHER POWER LEVELS (MEGAWATTS)

- RADIATOR IS VERY LARGE (ACRES) AND IS THE DOMINANT MASS.
- ADVANCED VERY LIGHT CONCEPTS ARE REQUIRED

RADIATORS

- LIQUID DROPLET & CURIE POINT (MAGNETIC)
- FREE LIQUID SURFACE ROTATING DISKS
- MOVING BELTS (DRY OR WET)
- SPHERICAL MEMBRANE
- EXPANDABLE (PARTY WHISTLE)

HEAT EXCHANGERS

- DIRECT CONTACT OF FLUID STREAMS
- SPRAY FED CAPILLIARY WICKED SURFACES
- SINGLE PHASE JET IMPINGEMENT
- ENTRAINED MICROENCAPSULATED PHASE CHANGE MATERIAL IN FLUID

LIQUID METAL SYSTEMS

- EM PUMPS
- SINGLE & TWO PHASE LOOPS, HEAT PIPE RADIATORS

Figure 20.

CONCLUSIONS

- o SPACE STATION TECHNOLOGY IS NECESSARY PRECURSOR BUT DOES NOT MEET S/C 2000 NEEDS
  - - LIFE, HIGH HEAT FLUX, LONG TERM CRYO AND SURVIVABILITY
- o ADDITIONAL BASIC AND APPLIED RESEARCH REQUIRED
  - - FLUID/MATERIALS COMPATIBILITY, TWO PHASE SYSTEM MODELLING
- o SCALING IS KEY ISSUE
  - - MUST DEFINE ACCELERATED LIFE TEST CRITERIA
  - - TWO PHASE SYSTEMS REQUIRE 0 G TO 1 G CORRELATION
  - - SYSTEM SIZE MAY PRECLUDE FULL SCALE GROUND TEST
- o ADDITIONAL GROUND TEST BEDS ARE REQUIRED
  - - MATERIALS COMPATIBILITY
  - - COMPONENT LIFE TESTS (HEAT PIPES, PUMPS, VALVES ETC)
  - - SYSTEM LIFE TESTS OF TOTAL HEAT TRANSPORT LOOP
- o COMBINED SPACE ENVIRONMENT TESTS OF MATERIALS

Figure 21.

IMPLEMENTATION POLICY

- o ORGANIZE SMALL SPACECRAFT THERMAL SYSTEM STEERING COMMITTEE
  - - MILITARY, NASA AND INDUSTRY PARTICIPANTS
  - - YEARLY MEETING TO ASSESS NEED, TRENDS AND RECOMMEND NEW INITITIVES
- o ESTABLISH AN X-1,2,3 EXPERIMENTAL SPACECRAFT PROGRAM ANALOGOUS TO X SERIES AIRCRAFT
  - - GENERALLY LAUNCHED ON ELV'S BUT OCCASSIONALLY COULD USE SHUTTLE FOR RETRIEVAL E.G. LDEF
- o RE-EXAMINE ROLES / FUNDING OF UNIVERSITIES, NAT LABS, SMALL BUSINESS & AEROSPACE COMPANIES
- o COMPILE A HAND BOOK OF EXISTING AND PLANNED U.S. TEST FACILITIES FOR THERMAL SYSTEM VALIDATION
  - - VACUUM CHAMBERS
  - - COMBINED ENVIRONMENTS
  - - COOLING LOOP TEST BEDS
  - - HEAT PIPE LIFE TESTS
  - - ETC
- o DETERMINE IF ADDITIONAL NATIONAL MULTI-USE TEST FACILITIES ARE DESIRABLE

Figure 22.

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ELECTRICAL POWER WORKING GROUP REPORT

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1. INTRODUCTION

As indicated in the observations and recommendations of the Spacecraft Systems Working Group, the Electrical Power Subsystem represents a high-leverage area for spacecraft bus mass reduction and resulting payload fraction improvement. While mass reduction benefits all mission types significantly and directly, improvements in several other performance parameters, including deployed area and radiation hardness, are important in specific applications. Life, reliability and cost, while acceptable for current power systems, could be improved and should certainly not regress as low-mass technologies are developed and implemented.

Within this context, the Electrical Power Subsystem Working Group assessed the status of and need for power technologies for Spacecraft 2000 and identified development programs required to establish an achievable and competitive technology base for spacecraft of the 21st century. This report summarizes the results of the Working Group efforts, including recommendations and the underlying rationale.

2. SCOPE AND OBJECTIVES

The missions and spacecraft covered by this assessment were limited to the following primary groups, based on Steering Committee guidance provided at the start of the Workshop:

- GEO Satellites
- GEO Platforms
- Polar Platforms
- Planetary Missions

This mission mix led to selection of 50 kW as the maximum payload power level. This leaves out power systems based SP-100 technology, several SDI missions, and very-high-power planetary spacecraft. Space Station and related systems are excluded since their power hardware is currently being developed, but their contribution to the technology base is recognized.

Other constraints imposed on the scope include that technologies to be considered should have reasonably broad applicability to a range of missions; that unusual power technology requirements for unique missions should receive dedicated development outside the Spacecraft 2000 initiative; and that recommended technologies should have the potential for readiness early in the 21st century.

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The overall objectives of the EPS WG study were:

- Identify critical power subsystem needs, issues, and limitations
- Identify promising technologies and their benefits
- Recommend development and validation programs, and possible government/industry roles

3. APPROACH

Because of the diversity of power technologies, and the size of the EPS WG, the group was divided into four panels as follows:

- Power System
- Power Generation
- Energy Storage
- Power Management and Distribution

Each panel independently addressed its area in accordance with the objectives, but periodic brief overall WG reviews were held to provide opportunity for cross-critique, coordination, and discussion. The typical assessment approach for each panel was:

- Identify power subsystem technology selection criteria
- Identify and assess key issues in current technologies
- Define performance limitations of current technologies
- Identify promising new technologies and their benefits
- Assess technology readiness date vs development support
- Determine need for and status of development programs

Several key considerations were used to guide the technology and development requirements assessment, with the underlying goal of maximizing mission- and cost-effectiveness:

- Commercial/NASA/Military design practice differences
- Desirability and feasibility of standardization
- Autonomous operation
- Safety, reliability, and survivability

- Performance, mass and life vs cost
- Manufacturability, testability, serviceability, and supportability

4. POWER SYSTEM

The Power System panel addressed broad issues that affect overall power subsystem design, development, implementation, operation, interfaces, and user accommodation. The general areas addressed were:

- Commercial/NASA/Military practice
- Power levels
- User power preferences & needs
- Source technology applicability
- Hardware modularity & standardization
- Serviceability/maintainability
- Power system test beds
- Automation technology
- Orbit and mission factors
- Operating voltages, dc vs ac
- Central vs local regulation
- Topology standardization
- Growth accomodation
- Integrated power system modeling
- Test technology
- Expert systems applications

4.1 Key Issues Definition

From the above list of items the following key issues were identified which represent needs that are inadequately addressed by current development of power system technology:

Technology Key Issues	Design Philosophy Key Issues
o Automation technologies	o Standardization
o High-voltage (>150 V)	o Modularity for commonality
o Total-system modeling tools and techniques	o Modularity for serviceability and maintainability
o Expert systems technologies	o Utility approach to power distribution
	o Growth capability/compatibility

The technology key issues represent areas where specific hardware and software development is needed. The philosophy key issues are concerned with policy and approach: the general framework and constraints that apply to the development of power system technologies, including power generation, energy storage and power management and distribution hardware.

4.2 Technology Development Recommendations

Automation

Cost effectiveness of future space systems will depend strongly on minimization of real-time spacecraft operation from the ground. As satellite power systems become larger, more sophisticated and optimized, operational complexity is likely to increase. In addition, the detection, diagnosis, correction, and management of fault conditions becomes more complex and demanding. The growing inventory of operational spacecraft will magnify this problem.

Interplanetary missions have a particularly strong need for power system automation because of the long reaction time and resulting increased vulnerability to fault conditions. For earth-orbiting missions automation could be implemented on-board the spacecraft or on the ground via telemetry and command links. The latter approach still involves time delay and is itself vulnerable to interruption and faults. Thus, on-board automation is clearly a necessary technology for Spacecraft 2000, and is viewed as enabling for the larger power systems. It will lower operations cost and risk and improve system performance.

Automation philosophy is being developed for Space Station systems. It is recommended that similar development be conducted on automation for unmanned and non-maintainable space systems, taking advantage, where appropriate, of Space Station data. In particular, the general power system management philosophy should be defined in an initial study. This general approach should cover interplanetary as well as earth-orbiting spacecraft, and a range of power source and energy storage alternatives. As a next step, algorithms and software should be developed and verified in ground-based hardware test bed.

High-Voltage Power Distribution

Low voltage dc power distribution has been used in virtually all spacecraft to date. For the Space Station and related systems, a 20 kHz, 440 V distribution system will be developed. The age-old question of what the best distribution technology is has not been conclusively answered, however, for all applications. The high voltage level on the station is driven primarily by mass of the distribution lines, and 20 kHz ac was selected for mass-efficient conversion to other power types.

For dimensionally smaller spacecraft the distribution of power at the generation voltage, which may be on the order of 200 V for higher-power systems, is quite mass-efficient and little would be gained by conversion to higher voltage ac power for distribution. Individual payloads can then provide local conversion to the specific needs of each payload with efficient, high-frequency converters.

It is therefore expected that significant demand as well as payload customer preference will exist for the foreseeable future for high voltage power systems. Competitiveness in the international marketplace will also likely require the capability for producing these systems. Availability of both ac and dc options would provide a flexible, competitive technology base for Spacecraft 2000.

The recommended development effort would consist of definition of appropriate standards and development/adaptation of devices, switchgear, and conversion equipment for high voltage operation, taking advantage where possible of developments of similar hardware for the photovoltaic subsystem source bus on the Space Station.

System Modeling Tools and Techniques

The increased complexity and size of power systems will make it increasingly difficult to validate system performance prior to hardware fabrication, and will escalate the cost of dedicated test beds for each application. In addition, optimization of the overall system design requires more complete models than currently available.

It is recommended that development be initiated of an integrated power system model that has a high degree of modularity, flexibility, and adaptability. This model would serve as a standard tool for design and analysis of Spacecraft 2000 and related power systems. It would permit detailed iterative analysis and performance evaluation at a very early stage of hardware design. Most initial iterations could then be conducted analytically, so that a significant amount of breadboarding and other developmental hardware efforts could be avoided, with resultant cost savings. The model should be verified on a generic test bed. Combined with a reasonable degree of standardization, this model could significantly reduce the cost of power system design, development, and redesign.

Expert Systems

Expert systems for the management of space power systems are a natural follow-on to the automation and modeling efforts. Automation techniques and software currently envisioned will be limited in their ability to deal with highly complex systems and real-time decision making will not accommodate complex rules. Application of expert systems to the EPS will enable greater operational independence, optimization, and interfacing with higher-level expert systems governing overall spacecraft and payload operations.

While this capability should flow out of the automation and modeling tasks, it is recommended that initial studies be performed to establish a framework of requirements, system management philosophy, and hierarchies applicable to an EPS expert system. This will serve as guidance for the other tasks, so that the eventual transition to expert system development and implementation will be evolutionary in nature, rather than requiring a complete overhaul of the approach.

4.3 Design Philosophy Definition

The design philosophy area addresses issues that do not require specific technology developments, but rather studies to define overall design guidelines for space power systems and components. The main drivers behind these issues are cost-effectiveness in DDT&E, production, and implementation of space power systems, and providing flexible user power.

Standardization and Modularity

The concepts of standardization and modularity are strongly related and must be addressed in an intergrated fashion. It is recommended that studies be conducted to establish guidelines for standardization and modularity based on probable payload power requirements, servicing and maintenance concepts and scenarios, and mission type distribution. These guidelines will necessarily evolve as Spacecraft 2000 systems studies achieve increasing degrees of definition.

Standardization. Several standards exist today for space power systems at low voltage. Similar standards should be developed for higher-power, high-voltage systems to promote cost-effective development and provide guidance to advanced systems planning for Spacecraft 2000 in both payload and bus areas. These standards should be developed in a cooperative, iterative fashion by NASA and industry, and retain sufficient early flexibility to absorb information and refinements from hardware efforts, and other programs such as Space Station.

In hardware development a certain level of standardization should also be considered to improve cost effectiveness. The concept of a modular EPS approach with several standard component sizes should be re-evaluated, and may be feasible for platform-type satellites. To avoid significant mass penalties and unnecessary margins, however, a study should be made of the probable payload power requirements spectrum for Spacecraft 2000, so that the level of standardization and modularity can be intelligently selected.

Modularity for Commonality. This concept concerns selection of EPS components module sizes that by replication can meet the power requirements of individual missions, while minimizing mass penalties and production cost. This concept can even be extended to subassemblies within components.

Modularity for Serviceability/Maintainability. Space systems of the Spacecraft 2000 generation should be designed for maintainability and serviceability. Design of the EPS should allow for normal and safe operation with temporary absence of components during servicing operations, which suggests component module sizing and replication as well as design features and constraints.

Utility Type Power Distribution

The utility approach to power distribution is an important element of ensuring that Spacecraft 2000 power systems have broad applicability and a flexible payload accommodation interface. It implies distribution of one type of power with local regulation and processing at the payloads to suit their specific needs. This will provide a clean, predictable power interface. As part of the standardization studies this approach should be addressed in order to identify specific implementation issues and preferred configurations.

Growth Capability and Compatibility

An integral element of modularity and standardization is the feasibility of growing power subsystems to accommodate additional payloads. This is a natural requirement for multi-payload platforms in particular. Cost-effective growth capability is tied to modularity issues and should be addressed as part of the studies that define the guidelines in that area. Growth accommodation must also be allowed for in the design of EPS components to permit growth with newer technologies alongside still operational older hardware. This established a requirement for "transparency" of technologies: interfaces must be established and defined to isolate the major EPS elements from the peculiar characteristics of interfacing elements. Standardization of power bus performance parameters must consider this very carefully so as not to "shut out" new technologies.

5. POWER GENERATION

The Power Generation Panel considered photovoltaic, solar thermal dynamic, and nuclear power source technologies in the context of Spacecraft 2000 applications. Given the size and types of missions involved, the overall judgement was that the emphasis should be on improvements in photovoltaic technologies.

5.1 Solar Dynamic Systems

In the solar thermal dynamic area, significant development will occur as part of the Space Station program. This may spin off technology that can be scaled down to power levels appropriate for Spacecraft 2000, but specific development should await results of the Station efforts. On-going Stirling engine development should be continued to provide an advanced high-efficiency conversion cycle alternative.

5.2 Nuclear Systems

Nuclear reactor technology may have application in higher-power interplanetary missions. This possibility should be addressed by studying SP-100 derived technology and other small reactor concept designs in the context of projected mission requirements. Hardware development would be conducted most likely outside the Spacecraft 2000 scope since this would be a rather specialized application.

5.3 Photovoltaic Systems

Photovoltaics offers significant potential for improved performance in terms of specific power (W/kg), primarily by decreasing solar cell thickness and by improving array construction technology. Development of high-efficiency cells will provide additional mass leverage. Cost of production can be improved by using large-area cells for silicon or concentrator cells for gallium arsenide (GaAs). Life performance improvements are feasible through the use of advanced cells which are not significantly affected by radiation environments. Specific recommendations will be discussed in more detail below.

Specific programs recommended for consideration under the Spacecraft 2000 initiative are:

- Lightweight Silicon Array
- Gallium Arsenide Flight Panel
- High Efficiency Solar Cells
- Indium Phosphide Solar Cells
- Advanced Concentrator Arrays
- Modular Solar Array

The first two programs form an integrated effort to systematically improve array performance capability by phasing in advanced technology in a logical, timed, but aggressive fashion. They develop hardware based on technology already within reach. The cell programs are directed at device technology R&D and demonstration, with the end product to be eventually retrofitted into the lightweight array technology.

Lightweight Silicon Array

Typical specific power capability of current advanced arrays is about 30 W/lb. A JPL-sponsored program is now underway at TRW to develop technology at the 60 W/lb level through the use of thin cells. The selected configuration uses relatively small cells and significant optimization of the array structure is not part of the program scope. It is strongly recommended that a follow-on program be conducted to incorporate large area cells and perform added optimization of the structure to arrive at about 75 W/lb or better.

Gallium Arsenide Array Technology

GaAs cells have significantly improved efficiency than Si but are currently built at relatively high thickness (12 mil) and thus represent a mass penalty negating the efficiency gain. The potential for improvement will be realized with thin cells. Projected capability with 2-3 mil GaAs cells retrofitted into the lightweight array will be 100 to 110 W/lb. To establish readiness for application in a timely fashion, it is recommended that a two-phase development program be conducted. The first phase would establish and demonstrate GaAs cell laydown, interconnection and assembly techniques using 12 mil cells and flexible array technology, and include thermal cycle testing. The second phase, building on this technology and the lightweight Si array results, would include module fabrication using thin GaAs cells.

High Efficiency Solar Cells

Further improvements in specific power can be obtained from high-efficiency cell technology. Achieving the GaAs efficiency goal of 26% could yield 140 W/lb, and multi-bandgap cells at 30-35% could reach 180 W/lb if they can be produced at competitive thickness levels. NASA should consider funding selected high-potential aspects of this work to accelerate availability of these devices.

Indium Phosphide Solar Cells

Indium Phosphide (InP) solar cells promise exceptional resistance to radiation damage. This can be a significant advantage in particular for polar orbiters. It is recommended that NASA support this technology with research funding to evaluate feasibility, optimization potential, and demonstrate capability for about 18% efficiency and radiation resistance/annealing properties.

Advanced Concentrator Arrays

Concentrator arrays can make the high efficiency of GaAs cells available in terms of area reduction and, while GaAs cells are still expensive, at a potentially reduced cost. Significant power density improvements are less likely with this concept because of the rigidity requirements for the arrays, caused by the tight pointing requirements. It is recommended that NASA maintain current in the technology and conduct specific studies to evaluate whether NASA mission requirements exist that may benefit from the concentrator approach, and conduct appropriate development to support such mission requirements.

Modular Solar Array

Current solar arrays are typically custom designed for the specific application, resulting in significant non-recurring cost. To explore opportunities for cost reduction, a study is recommended of modular solar array concepts, in concert with the power system standardization and modularity studies. The objective should be to define and evaluate approaches to modularization for commonality, maintainability, growth and interface standardization, and establish a module sizing rationale. Study results should verified at the component level and then be fed into lightweight array programs.

6. ENERGY STORAGE

The Energy Storage Panel considered the following energy storage technologies and divided them into the three categories shown below:

Current

- nickel-cadmium
- nickel-hydrogen
- regenerative fuel cell (separate stacks, dynamic transport)

Near Term Advanced

- sodium-sulfur (beta)
- regenerative fuel cell (separate stacks, passive transport)
- rechargeable lithium

Far Term Advanced

- regenerative fuel cell
    - single cell
    - solid oxide
    - anhydrous H2/halogen
- sodium-sulfur (glass)
- lithium batteries
- polymer batteries

- o flywheels
- o tethers

In general, the Panel recommends that NASA place the least emphasis on the current technologies, the most on the near term advanced technologies, and an intermediate amount on the far term advanced technologies. The one exception is a recommendation that NASA emphasize ground testing of nickel-hydrogen cells to a low earth orbit regime because of the importance of the technology to Space Station. The Panel recommended sodium-sulfur batteries and simpler regenerative fuel cells for the most emphasis over the next several years. Finally, the Panel recommends that NASA sponsor moderate and steady research effort among the far term advanced technologies until preferred approaches emerge.

6.1 Current Technologies

These are mature technologies which have either transitioned to operational use, or, in the case of regenerative fuel cell, the major components (fuel cell and electrolysis stacks) are mature and the system is ready for engineering development for specific applications by 1990. The usable specific energies of these technologies range from 3-12 watt-hours/pound (Wh/lb) for nickel-cadmium, to 6-16 for nickel-hydrogen and somewhat higher for regenerative fuel cells.

Nickel-Cadmium Batteries

Nickel-cadmium batteries are the most mature of the technologies considered and are the least likely to yield dramatic improvements in specific energy with further development. The key to improved performance in nickel-cadmium batteries is increased depth-of-discharge for the longer cycle life missions which, in turn, is dependent on improved nickel electrodes. The development of improved nickel electrodes is the object of work sponsored by NASA Lewis Research Center. This work should be continued because it has been productive and is likely to continue to yield the greatest benefit for the least cost.

Nickel-Hydrogen Batteries

Nickel-hydrogen batteries based on IPV (individual pressure vessel for each cell) have transitioned into operational use in high orbits where the limited cycle life requirements make the present limited data base adequate to make the selection. The data base for low orbit use needs to be improved to provide more reliability and confidence level data and to better define cycle life capabilities at various depths of discharge. Since IPV nickel-hydrogen cells have been selected for use on the Space Station, it will be necessary to further develop the data base for low orbit operation. NASA should participate with the Air Force in a low orbit test program already being set up at the Naval Weapons Support Center at Crane, Indiana.

The design and manufacture of IPV cells is fairly well established, although incremental improvements are still being made. The design and manufacture of bipolar modules is incomplete and should be continued if the unique advantage of high rate capability is to be realized.

Improvements in nickel electrodes that would allow deeper depths of discharge could substantially improve usable specific energy, particularly for low orbit missions such as Space Station. Unlike nickel-cadmium cells, nickel-hydrogen cells can also improve their specific energy if the nickel electrodes can be made thicker (e.g. thickness increased from 29-35 mils to 60-80 mils). Again, improvements in both nickel-cadmium and nickel-hydrogen technology depend on improvements in the nickel electrode. Continued investment in nickel electrode technology will yield the greatest benefit at the lowest cost.

Regenerative Fuel Cells (Active Water and Thermal Management)

The critical components (separate fuel cell and electrolysis cell stacks) of a low temperature, hydrogen-oxygen, regenerative fuel cell systems are well established. Engineering development could combine these components into systems (using active components for product water and thermal management) by 1990. The reliability of such systems is suitable for low orbit manned missions where maintenance and resupply are possible. It is not suitable for missions where maintenance and resupply are not possible.

Much of the basis for the development of this system was in anticipation of its use on Space Station. The selection, by Space Station, of solar dynamic and nickel-hydrogen technologies instead, reduces the incentive for near-term development of this approach (i.e. with active components for water and thermal management). There is, however, a basis for further development of low temperature, hydrogen-oxygen regenerative fuel cell systems that use passive means of water and thermal management as discussed in the next section.

6.2 Near Term Advanced Technologies

All near term advanced technologies offer usable specific energies in the range of 25-50 Wh/lb. The technologies of critical components (cells and stacks) have been under development for many years and are well advanced but require further development. They can have technology readiness dates in the mid-1990s if properly supported.

Sodium-sulfur Batteries (Beta Alumina Electrolyte)

Sodium-sulfur batteries have the best combination of high usable specific energy and advanced technology status. The high usable specific energy is the result of three factors: (1) the high specific energy of the cells (75 Wh/lb), (2) slightly higher charge-discharge efficiency than nickel based systems resulting in reduced solar array size and weight, and (3) high temperature operation (350 C) which dramatically reduces radiator size and weight. Individual cells have operated for more than 6000 cycles and for 2-3 years. Adequate calendar life remains to be demonstrated. The main problems are degradation of the beta" alumina electrolyte and corrosion of the container, but progress has been steady in both areas.

The Air Force, after an exhaustive study of other battery and fuel cell alternatives dating back to 1979, has selected sodium-sulfur for their next generation space battery. The Air Force program is comprehensive, covering cells and batteries for high and low orbits. Work by NASA in the sodium-sulfur battery area should be carefully coordinated with the Air Force to prevent duplication of effort.

Regenerative Fuel Cells (Passive Water and Thermal Management)

There are concepts for, and some demonstration of, low temperature, hydrogen-oxygen regenerative fuel cell systems which use passive techniques of water and thermal management. Systems based on passive water and thermal management techniques have the potential for the higher reliabilities needed for use in unmanned missions. If these techniques can be implemented in lightweight hardware, specific energies comparable to sodium-sulfur and rechargeable lithium batteries should result. In addition, hydrogen-oxygen regenerative fuel cells offer higher peak power capability than either of the batteries and the possibility of further weight savings by integration with other spacecraft systems such as hydrogen-oxygen propulsion.

The Panel recommends that NASA continue development of regenerative fuel cells emphasizing passive techniques of water and thermal management.

Rechargeable Lithium Batteries

Various lithium-based rechargeable batteries offer high specific energy at potentially low cost and with cycle life suitable for high orbit missions. Small commercial cells of less than one ampere-hour capacity already offer about 25 Wh/lb and up to 3000 cycles. Lithium-metal sulfide cells offer 32-42 Wh/lb. Higher specific energies are likely with development. The Energy Storage Panel did not have a lithium battery specialist, and does not make specific recommendations in the lithium battery area.

6.3 Far Term Advanced Technologies

The far term advanced technologies generally have the potential for very high usable specific energies - some greater than 50 Wh/lb, but have technology readiness dates of 2000 or beyond. The development of virtually all has been slowed mainly by materials problems. Due to the nature of the materials problems involved, it is difficult to predict where future development might lead to a breakthrough in device practicality. Nevertheless, these technologies represent the most likely sources of advanced energy storage systems for the next century.

The Panel did not have specialists in the areas of lithium batteries, polymer batteries, flywheels of tethers; and does not make recommendations specific to individual technologies in these or the other areas. The Panel does recommend that NASA sponsor a broad and stable, moderately funded program of investigation of these, and possibly other, far term advanced technologies to provide a technology base for future developments.

7. POWER PROCESSING, MANAGEMENT AND DISTRIBUTION

The Power Processing, Management and Distribution Panel was concerned with the following general types of issues:

Distribution Power

- AC, Frequency & Voltage
- DC, Voltage
- Architecture
- Multiple Buses

User Interface

- User-Friendly
- Standardization

Processing Technology

- Converters and Inverters
- Packaging Technology

Component Technology

- High Voltage
- High Power
- Semiconductors
- Capacitors

Protection Devices

- RPCs
- Hybrid Switchgear

Automation

- Hardware
- Software

The conclusions and recommendations in this area are consistent with, and in some cases overlap, those of the Power Systems Panel.

Recommended technology areas for development and study under Spacecraft 2000 auspices are:

- Primary power distribution - high voltage data base
- High power, high voltage switch gear
- Power system automation technologies
- AC distribution system component development
- Integrated analog/digital devices

It is recognized that many of these technologies are planned to be developed as partof the Space Station program. Significant benefit should be derived from those efforts since they push the technology to higher power levels and greater degrees of automation. However, it is generally recommended that NASA assess the suitability of the Space Station designs and hardware to the needs of more specialized, unmanned, and potentially non-maintainable vehicles that may be part of the Spacecraft 2000 family. It is expected that significant upgrades in mass and reliability performance will be desirable and possible. Appropriate development programs should be undertaken to accomplish these upgrades by the late 1990s.

Primary Power Distribution - High Voltage Data Base

Distribution of power at high voltage reduces the size and mass of the harness, a significant benefit for higher power missions. For Space Station the high-voltage dc power source bus operates at a conservative 160-200 V; higher voltage, although desirable, was avoided because of the lack of firm data on plasma interactions. In general, the available data are limited, conflicting, and strongly dependent on test technique.

With the broader application of high voltage dc and ac systems it is essential that sufficient credible data be accumulated to help define limits of operation, component design considerations and margins, and support selection of optimal architectures. With such a data base, full advantage of the safe operating range can be taken with resulting greater benefit. It is recommended that a comprehensive effort be undertaken to establish this data base, including flight tests as appropriate.

High-Voltage Switch Gear

High-voltage switch gear is not currently available for high reliability space applications. High-voltage spacecraft will require programmable, resettable solid state remote power controllers for power system management, fault isolation, and reconfiguration.

While such elements are now baselined to be developed on the Space Station program, they will be primarily directed at its high power levels only, without optimization for medium power levels and highly mass-critical spacecraft. To ensure that optimized high voltage ac and dc switch gear are available for the Spacecraft 2000 generation, specific development and optimization for medium power levels is recommended. Such efforts should take full advantage of Space Station switch gear technology development, and make next-generation improvements in device capability and reliability.

Power System Automation Technologies

Automation technologies will be driven by autonomy and survivability needs. Automatic monitoring of Power Subsystem performance and performing self-test operations will be an essential element of greater spacecraft autonomy. Virtually all automation will be accomplished via software, with only those items still hardwired that require immediate response, such as fault isolation functions. Software-based automation will allow use of standardized hardware, which can be programmed and reprogrammed for suitable operating parameters and limits.

Key hardware elements of automation are sensors and built-in test equipment (BITE). These must be developed for general purpose spacecraft applications beyond technology planned for Space Station. It is recommended that NASA conduct detailed studies of requirements for sensors and power subsystem BITE for Spacecraft 2000 with Space Station technology as a baseline and conduct further development to extend that technology to Spacecraft 2000 needs.

AC Distribution System Components

AC distribution at 20 kHz has been baselined for the Space Station program. It is expected that larger spacecraft will use distribution systems based on this technology. For moderate power levels, optimization of transmission line design and reduction of connector mass and complexity are particularly important to the viability of ac power on future spacecraft. Impedance behavior of ac harnesses in complex networks also requires further understanding, along with better test, modeling and simulation techniques.

These areas should be explored with Space Station technology as a point of departure, defining improvements and optimization required for broader satellite application, and appropriate development efforts to achieve readiness by the year 2000.

Integrated Analog/Digital Devices

Automation of power subsystems requires extensive interfacing of analog and digital devices to form the link between analog sensors and data/control functions. High-frequency power conversion using discrete components is complicated due to uncontrolled parasitics. Integration of analog and digital devices on a single chip is important to minimizing mass and volume as well as parasitics and other interference problems. Analog/digital device integration development is proceeding in commercial applications, but does not address several aspects that are key to successful space devices, such as thermal control, isolation, and multiple power device topologies.

It is recommended that NASA conduct a study to develop topologies for integrated analog/digital devices appropriate to applications in spacecraft power subsystem components. These topologies should cover multiple on-chip power structures, on-chip optical interfacing, and thermal management approaches. Development of prototype devices for test and evaluation should follow to establish readiness for fligh. hardware development by the early 1990s.

8. ADDITIONAL RECOMMENDATIONS

8.1 Flight Tests

It is recommended that brief flight tests, most likely on the STS Orbiter, be conducted to characterize plasma interactions with high voltage power subsystem elements, such as solar arrays and distribution lines. No strong necessity is seen for extended flight tests in the near future.

8.2 Terrestrial Test Beds

Establishment of a terrestrial electrical power system test bed is seen as a high priority item. This test bed should have the flexibility and modularity to accept hardware of different power ratings and types. Its purpose will be the experimental verification of new devices and hardware concepts, as well as software for power system control. Adaptation of test bed efforts being undertaken for the Space Station program should be considered, for cost effective implementation of the proposed flexible test bed.

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TELEMETRY, TRACKING, AND CONTROL WORKING GROUP REPORT

Richard Campbell, Chairman
Lockheed Missiles & Space Company, Inc.

L. Joseph Rogers, Cochairman
NASA Goddard Space Flight Center

The TTC Working Group consisted of 12 people from NASA and industry. A good representation from industry was present, encompassing both commercial and aerospace interests. The Chairman of this group was Dick Campbell from Lockheed Missiles and Space Company; the Co-chairman was Joe Rogers from NASA-Goddard. The group was chartered to identify the technology needs in TTC for a spacecraft in the year 2000.

TTC WORKING GROUP

NORMAN LANTZ	AEROSPACE CORPORATION
SIDNEY SKJEI	GTE SPACENET
DON NOVAK	COMPUTER SCIENCES CORPORATION
RICHARD CHITTY	FAIRCHILD SPACE COMPANY
JOE BALOMBIN	NASA-LEWIS
ERIC HOFFMAN	JHU/APL
G. "ART" ANZIC	NASA-LEWIS
FRED HAWKES	GOULD COMPUTER SYSTEMS
STANLEY CLARKE	TRW SPACE COMM. DIVISION
JOE ROGERS, CO-CHAIRMAN	NASA-GSFC
REGGIE HOLLOWAY	NASA-LCRC
DICK CAMPBELL, CHAIRMAN	LOCKHEED MISSILES AND SPACE COMPANY

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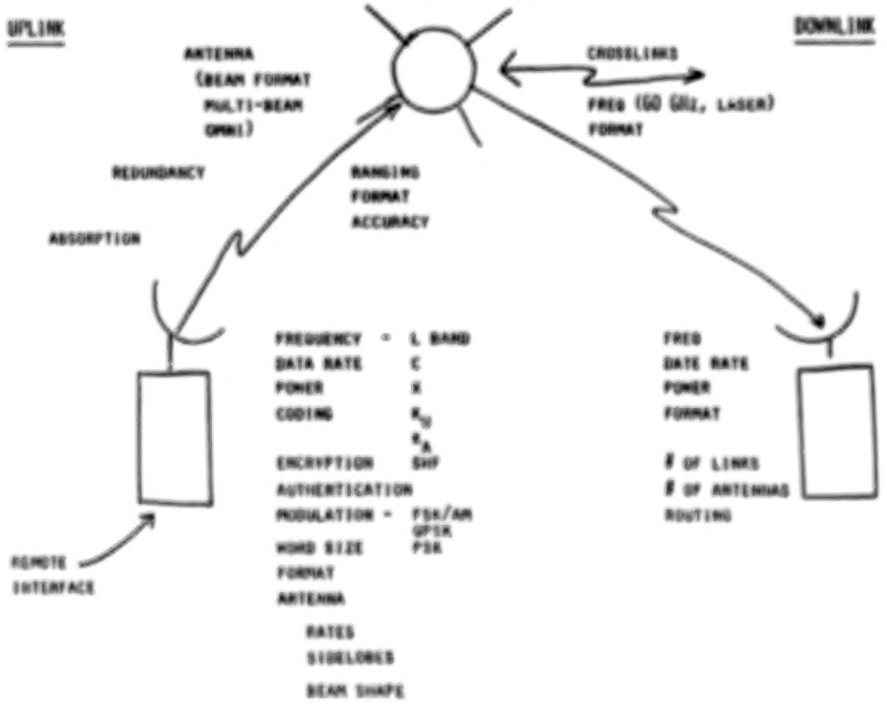
TYPICAL TTC SYSTEM CONCEPT

The first action of the working group was to define what it was trying to accomplish. It was concluded that the group should address just TTC and not communications except in the context of TTC. This was in adherence to the ground rules provided to the working group. A typical TTC system was defined, the elements being an uplink and a downlink to the spacecraft, with potential crosslinks to other satellites. The types of elements that were addressed included antennas, transmitters, and receivers. For antennas, several areas were considered such as how beams are formed, whether multi-beams are needed, the directionality of the beams, etc. The operating frequency was addressed, both in microwave and laser regimes. The format of the data and the accuracy of the data were considered, as well as the range of transmission reception. One interesting feature that was identified was that current TTC systems occupy a wide range of frequencies, encompassing L, C, X, KU, KA, and SHF frequency bands. A typical TTC system concept is shown in the figure.

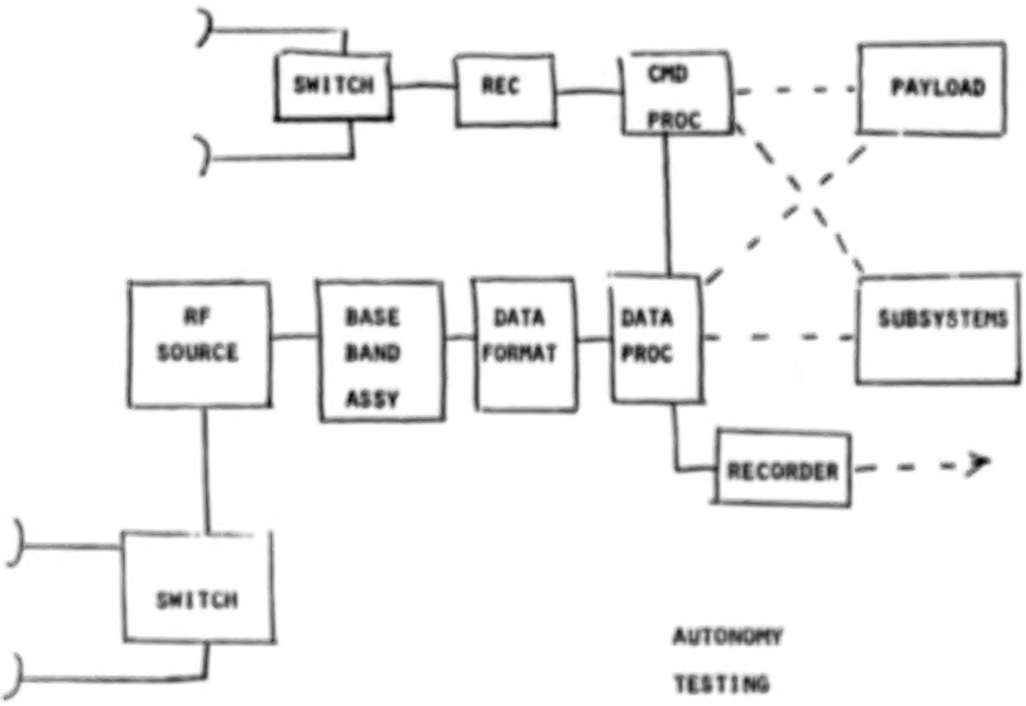
TYPICAL TTC SYSTEM CONCEPT



TYPICAL ON-BOARD TTC SYSTEM

The working group tried to define a typical on-board TTC system. The purpose of this was to provide a discussion mechanism to assure that the group addressed all components of a TTC system. A typical TTC system is shown in the figure. The elements that comprise it include antennas, switches, receivers, and transmitters. Included are processing functions to process commands which are then sent to the other elements of the spacecraft, and to process data received from those elements. A data recorder is typically needed to store data for later transmission or for on-board reference. The issues related to such a system include its autonomy, its testability, and its reliability.

TYPICAL ON-BOARD TTC SYSTEM



AUTONOMY
TESTING
RELIABILITY

TECHNOLOGY SELECTION CRITERIA

The working group tried to establish the criteria that would be used in identifying critical technologies. These are listed in the figure and include those general criteria that apply to almost all subsystems. Two criteria, however, specifically related to TTC are apparent which are not generally applicable to other subsystems. The first of these is the frequency assignment for the TTC system. This is an external driver beyond the control of the TTC designer. The other criteria that applies uniquely to TTC is the support system necessary to allow the TTC system to function. The availability and/or feasibility of such a support system is a key ingredient in technology selection.

TECHNOLOGY SELECTION CRITERIA

1. EXTERNALLY DRIVEN FUNCTIONAL REQUIREMENTS
    - TECHNICAL PERFORMANCE (PWR, DATA RATE, ETC.)
    - RELIABILITY
    - COMPATIBILITY
    - FLEXIBILITY/REFORMATTING
2. FREQUENCY ASSIGNMENT
3. SUPPORT INFRASTRUCTURE AVAILABLE
4. PHYSICAL PARAMETERS
5. COST
6. ENVIRONMENTS
7. MISSION LIFETIME
8. ON-ORBIT SERVICEABILITY

KEY TECHNICAL PROBLEMS

After assessing the design implications and the criteria to be used in technology selection, the working group then attempted to define the technical problems that face the TTC area. A significant TTC problem is that the communications spectrum is becoming overloaded. Users require higher data rates with increased bandwidth implications. More and more users are coming on-line, including NASA and DOD programs, commercial satellite systems, and terrestrial systems requiring frequency allocations. All of these users must be channeled into selected parts of the spectrum that are controlled by regulatory agencies such as WARC and the FCC. This crowding of the spectrum makes interference between users more and more an issue.

Another technical problem is the classic issue of reliability and survivability. A TTC system typically requires extremely high reliability. Because of this, the designer likes to continue to use proven concepts and is hesitant about using new technology developments. Another problem defined by the working group was that once installed, a TTC system tends to be inflexible. As with all subsystems, size, weight, power, and cost are continuing problems.

A number of problems exist with TTC data. Users are demanding greater accuracy and higher resolution. Data compression techniques are often inadequate, and the processing and coding could be improved. Storage of the vast amounts of gathered data continues to be a problem.

The working group was unanimous in the opinion that TTC systems need to have more autonomy. Current problems include lack of fault detection and correction capability, and automatic operation of the TTC. It was felt that spacecraft generally should be capable of performing their own navigation function, thereby minimizing tracking support.

The working group identified another problem involving the inability to test a TTC system in a space environment prior to its actual utilization as the primary system of a spacecraft.

A final problem that was identified was the lack of design standards for TTC. Everybody designs to their own requirements without regard to other applications. This results in a multitude of designs and typically causes developed items to be inapplicable for new applications.

KEY TECHNICAL PROBLEMS

SPECTRUM OVERLOAD

- HIGHER DATA RATES/MORE BANDWIDTH
- REGULATORY ALLOCATIONS
  - WARC
  - FCC/NTIA
- MORE USERS
  - NASA/DOD
  - COMMUNICATIONS
  - NON-SPACE APPLICATIONS
- INTERFERENCE

RELIABILITY/SURVIVABILITY/PROVEN CONCEPT

SIZE, WEIGHT, POWER

COST

FLEXIBILITY

- PRE-INSTALLATION
- POST OPERATIONAL STATUS

KEY TECHNICAL PROBLEMS (CONT)

DATA

- ACCURACY
- RESOLUTION
- COMPRESSION
- PROCESSING/ENCODING
- ERROR CORRECTING CODES
- STORAGE

AUTONOMOUS OPERATION

- FAULT DETECTION/CORRECTION
- AUTOMATIC OPERATION
- REAL TIME EPHEMERIS (NAV)

TESTING/TESTABILITY

STANDARDS

RECOMMENDATIONS

For each of the problems identified by the working group, recommendations were made for needed technology developments. These recommendations are listed on the following pages. After compiling this list of recommendations, the working group attempted to prioritize these in terms of their need. The prioritization scheme was to use 1 as the highest priority, 2 as a medium priority, and 3 as a lesser priority. Therefore, the recommendations shown have been priority ranked as shown.

For the spectrum overload problem, the working group recommended development of new devices for other frequencies such as the EHF and SHF bands, and the development of laser communications. It was felt that these developments were of the highest priority for solving this problem. The devices for development included antennas, power amplifiers, phase shifters, modulators, VHSIC receivers, detectors, and sources. Of lower priority but still important were the development of higher order modulation schemes. Additionally, it was felt that development of new interference reduction techniques would be beneficial to solving the spectrum overload problem.

For the problem of reliability and survivability, the working group felt that a space-based test platform should be available for proving new TTC concepts. The group felt that as designers, they would be more apt to consider new techniques if these techniques had already been proven in a space environment. The group also recommended establishing a consolidated, high reliability parts program that could be used by industry. The group recommended that standardized design specifications be established for industry to use. Included as part of these design specifications would be the definition of space environments which also addressed radiation hardness guidelines. The working group felt that different reconfiguration needs of satellites should be examined to try to establish a pattern for needed flexibility. It was not clear how this flexibility could be implemented, but it was unanimous that more flexibility in TTC systems was desired.

In the data handling problem area, the working group felt that new technology was needed with regard to data conversion. Higher speeds of conversion are necessary with more accuracy and higher resolution. To accomplish this, new conversion devices must be developed. The working group also recommended the investigation of new data reduction techniques and development of their corresponding error correction codes. New techniques are needed in the areas of source data reduction, data compression, and on-board data processing. Implementation of these new techniques may require the development of new TTC devices. A final recommendation in the data handling area was to develop higher density, higher access rate, data storage techniques. Promising areas include electronic storage, magnetic storage, and optical storage, or combinations thereof.

For the autonomous operation problem area, the working group recommended the development of automatic navigation systems for spacecraft. Some type of support system is required with the options being GPS stations, earth fixed stations, or other techniques. To accomplish automatic navigation will require on-board processing, receiving, and auto track antenna systems. To enable further autonomous operation, the working group felt that more effort should be conducted in improving automatic fault detection, diagnosis, and correction.

For the testing and testability problems associated with spacecraft, the working group recommended an assessment of emerging techniques for box and system level tests as they might be applied to the TTC subsystem. For the standards problem, it was felt that standard interfaces would go a long way toward making TTC components more applicable to subsystem designs. These standards should address both electrical and mechanical interfaces. It was felt that the development of standard architectures for TTC which were inherently fault-tolerant would be of significant benefit. With such architectures, developers of new spacecraft could implement their systems with the confidence that necessary building blocks would exist.

RECOMMENDATIONS

SPECTRUM OVERLOAD PROBLEM

1 • RECOMMEND DEVICE DEVELOPMENT FOR OTHER FREQUENCIES (EHF, SHF BANDS)

  - ANTENNAS (OMNI, PHASED ARRAY, MULTIPLE BEAM)
  - POWER AMPLIFIERS
  - PHASE SHIFTERS/MODULATORS
  - VHSIC RECEIVERS

1 • RECOMMEND LASER COMMUNICATIONS

  - DETECTORS
  - SOURCES

3 • RECOMMEND INVESTIGATION/DEVELOPMENT OF HIGHER ORDER MODULATION SCHEMES

3 • RECOMMEND DEVELOPMENT OF INTERFERENCE REDUCTION TECHNIQUES

RECOMMENDATIONS (CONT)

RELIABILITY/MATURITY/SURVIVABILITY

1 • RECOMMEND A TEST BED FOR PROOF OF CONCEPT

2 • RECOMMEND ESTABLISHMENT OF A CONSOLIDATED HI-REL PARTS PROGRAM

3 • RECOMMEND ESTABLISHING STANDARDIZED DESIGN SPECS (INCLUDING ENVIRONMENTS)

3 • RECOMMEND DEFINING RADIATION HARDNESS GUIDELINES AND PARTS DEVELOPMENT PROGRAM

FLEXIBILITY

3 • RECOMMEND STUDY TO DETERMINE WHAT THE RECONFIGURATION NEEDS ARE FOR VARYING PAYLOADS

DATA

1 • RECOMMEND IMPROVEMENT IN DATA CONVERSION TECHNOLOGY

- SPEED
- ACCURACY
- RESOLUTION

1 • RECOMMEND INVESTIGATION OF DATA REDUCTION TECHNIQUES AND CORRESPONDING ERROR CORRECTION CODES

- SOURCE DATA REDUCTION
- DATA COMPRESSION
- ON-BOARD DATA PROCESSING

1 • RECOMMEND ADVANCED HI-DENSITY/HI-RATE DATA STORAGE TECHNIQUE DEVELOPMENT

AUTONOMOUS OPERATION

1 • RECOMMEND DEVELOPMENT OF AUTOMATIC NAVIGATION SYSTEM

- SUPPORT SYSTEM (GPS, EARTH FIXED, OTHER)
- ON-BOARD SYSTEM (INCLUDING AUTO TRACK ANTENNA)

2 • RECOMMEND DEVELOPMENT OF FAULT DETECTION/DIAGNOSIS/CORRECTION CONCEPT

RECOMMENDATIONS (CONT)

TESTING/TESTABILITY

2 • RECOMMEND ASSESSMENT OF EMERGING TECHNIQUES FOR BOX AND SYSTEM LEVEL TESTS

(FULL COVERAGE TEST VECTORS, PRE AND POST LAUNCH)

STANDARDS

3 • RECOMMEND DEVELOPMENT OF TT&C INTERFACE STANDARDS

(ELECTRICAL AND MECHANICAL)

3 • RECOMMEND DEVELOPMENT OF STANDARD, FAULT-TOLERANT ARCHITECTURES

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DATA MANAGEMENT WORKING GROUP REPORT

Edward Filardo, Chairman
Rockwell International Corporation

David Smith, Cochairman
Jet Propulsion Laboratory

(Note: This is a summary of the oral presentation by Dave Smith of JPL)

The first slide (Fig 1) represents the membership of our working group. You can see the diversity of people from the industry and government segments. Ed Filardo was the Chairman and Dave Smith was the Co-Chairman.

The next slide (Fig 2) represents a summary of requirements for some missions in terms of both the I/O data rate in MBPS and the processor speed in MOPS (Mega-operations per sec). This chart will give you some idea of the range in fundamental computational requirements. For example, in the case of Galileo, we are talking about maybe a rather definite kick range of 1/2 MOPS and an I/O rate of about 1 Megabit per sec. As you move out to some of the more complex missions, as in the case of planetary missions like the Mars Rover, this requirement point moves out on the log scale until you get to about 5 MOPS for the processing with a comparable I/O rate level. And then as you go on out to some of the G & C (guidance and control) levels, the problems of Mars Rover move out at processor speed. Way at the top of the chart are some instrument requirements relating to EOS, where there is some data formatting that requires movement of data at around 200 MBPS or more. To try to process that data on board and get the data rate down from 500 to 600 Megabits, this kind of compression will require about 100 MOPS processing level. So to do data compression at this kind of rate, you try to have some sort of data handling on board the spacecraft in terms of a fiberoptic network or some other technology to handle the large I/O rate.

If you try to form a consensus of the needed processing rate requirements versus I/O rate it turns out you are kind of in a dead box, eliminating very far out things like on-board synthetic aperature radar processing. So you can see that we really need data storage devices that will handle up to a terabit. For Spacecraft 2000 we need data I/O fiberoptics networks that will handle rates of 200, 300, or 500 Megabits per sec and processors at least up to 10 Mops.

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There is a kind of gap in trying to get the processing speed, and NASA has been dependent on VHSIC technology, which is driven toward some of the military applications and not necessarily toward space. Also, this technology has some problems in terms of being single-hit upset sensitive and can not be used in space right now, although programs are in place to solve this and provide qualified VHSIC. NASA, and Harry Benz of Langley in particular, is trying to direct that program to solve some of our problems, but it should be noted that VHSIC has a ways to go.

The next chart (Fig 3) is a comment on improvement in flight qualified components and families for computing. Several of our group feel that instead of the 1750 instruction set or maybe a general purpose computer to do symbolics as well as numeric calculations, the instruction set for the commercial size is preferable. In order to get there, i.e. use commercial kinds of derivatives of processors and so forth, we have to flight qualify at least the components. One of the problems we have is that there is about six to ten years from getting a flight qualified processor or parts from where the technology has been inserted. So we need to develop some component technology which is fast, insensitive to total dose of radiation, and single hit upset insensitive. We feel there are a couple of approaches.

Sandia is building the 32000 chip set and the National 32000 chip set with their rad-hard process. That set should be available in the late 1990's, at least the 32 bit processor; and that could be switched to GaAs rather than the current CMOS. The expected result, if we stay with this program, is that you could get the 5 MIPS machine and components of a processor with feature sizes drawn again from the VHSIC program down to about 1 micron. We also need high density RAMS along that same vein too, with 4K RAMS the only thing available now; we need also to bring off some high speed CMOS logic family in terms of completing the electronics problem. So this is a base only; you don't have to do it with 32000 chips and we might equally put money into other schemes to get a processor in the 5-10 MIPS range.

For data storage (Fig 4), we said that at least a terabit capability is needed. The spacecraft requires this and in addition, support rates from 10 Megabits to a Gigabit level. For planetary missions, the magnetic tape technology development program or a derivative thereof will probably suffice to achieve lower power and weight. The optical disk storage technology needs to be brought along and flight qualified for improvement in speed and I/O buffering, however. We should have that kind of technology, terabit storage and rapid access by the year 2000.

Now, as we move ahead to Spacecraft 2000 and the desired 10 MIPS processor speed level, you get into parallel processing technology and the need for distributed operating systems that can manage fault tolerance (see Fig 6). These systems must have selective fault tolerant modes and be capable of doing high speed critical calculations. The development of such flexible operating systems would be a big payoff for Spacecraft 2000.

The next chart (Fig 5) concerns software development tools, which all of us agree is going to be a real necessity to keep the cost down for Spacecraft 2000. Software is coming to dominate our lives and especially those tools required for generating software requirements, design code, test procedures, and documentation. There is the question of software life cycle and software maintenance as the total number of lines goes up. We need a specific identification of these tools and their requirements. As the spacecrafts evolve from, perhaps a common to a more generic type you need to be able to change the associated software and update it with specific tools. We are dependent right now on space station and SDI for developing a lot of these tools and it will be necessary to find some way of transferring or adapting these tools to other planetary programs and earth-orbiting programs.

Now consider the slide on languages (Fig 7). The Space Station picked the ADA language. We looked at ADA and there are some shortcomings with this language. However, we think for Spacecraft 2000, ADA is still a good choice. We think some work needs to be done on compiler efficiency. ADA is not a really good real time language and has to be augmented with other special routines. There are some problems with interprocess communications. If you have to use ADA as a distributive processor, you may have to put these into the operating system rather than augment the language; this is a trade we will have to make. The objective is to get a higher order of language which would solve these problems and there is a need to study ADA extension versus standardizing on some other language. What those extensions are, will be very important to not only Space Station but to Spacecraft 2000.

The next slide (Fig 8) concerns fault tolerance and testing. Fault tolerance in the past had come from triplicating and voting with some watchdog timers and older concepts. We need to rethink these, especially in light of the new distributive processing systems. So SDI has brought this to focus and will depend on that to look at fault tolerance in a new light in terms of new ideas and architectures. Fault tolerant concepts need to be able to treat flexible connectivity of distributive machines and especially for distributive control.

What does that mean to fault tolerance now, with distributive control? You have to treat such things as brizantine failures (someone is lying on the voting). When you get down to very fault tolerant systems, those kinds of improbable or low probability occurrences actually now become significant. SDI is putting a lot of money and resources into this arena and we want to try and ride their coat tails as much as possible.

The next chart is on fiberoptics networks (Fig 9). There are good programs on this subject at both Langley and Goddard. Research is being done at 300-500 Megabits in fiberoptic networks. What needs to be done in addition to continuation of these programs is the work to continue to flight qualify the components and the protocols that go along with these systems. In particular, there are different kinds of electronic components that go along with that kind of network that have to be flight qualified. I have listed some of the components here, and again note we are trying to do from 300-500 MBPS low error rate FOLANS, which is the fiberoptic land network in spacecraft.

Figures 10a and 10b are on the subject of communications protocol. At these rates you need real time dedicated response, reliable communications, and of course, we are talking very high band width. These are some of the characteristics of that network and without any one of those it is prohibitive, but you need a simultaneous constraint solution to solve all problems. The current link protocols can not handle the 100-300 Megabit band rate in software, and it's too complex for hardware; so new protocols are needed and work should be done to bring that along. It should be noted that this is a fairly open area at this point.

We are concerned about security (Fig 11), and that has to be looked at right now as we are talking about the operating system. And we are also talking about embodying some security concepts into the early development stages for new protocols for the fiberoptics networks as it is very difficult to do it at a later stage of development. NASA's needs in this area should be carefully identified.

Finally, the last chart (Fig 12) is on technology evolvability. When you are trying to integrate high speed fiberoptics, processors, protocols, etc. you are going to need some sort of systems modeling. Every one of us agreed that we are lacking the systems tools to model such things as error rates and systems performance. These systems models are needed to look at the benefits and trades associated with technology evolution. If you want to replace your computer from the 16 bit to the 32 bit and move as the industry moves, you are going to have to design it to be transparent. That kind of system modeling is lacking. NASA needs a very firm planning program now to select and develop these tools. Whether there is funding from SDI or some other source, it needs to be a consistent plan put together by NASA.

DATA MANAGEMENT

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JERRY MUENCH, ODETICS
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Figure 1.

SPACE COMPUTATIONAL REQUIREMENTS SUMMARY

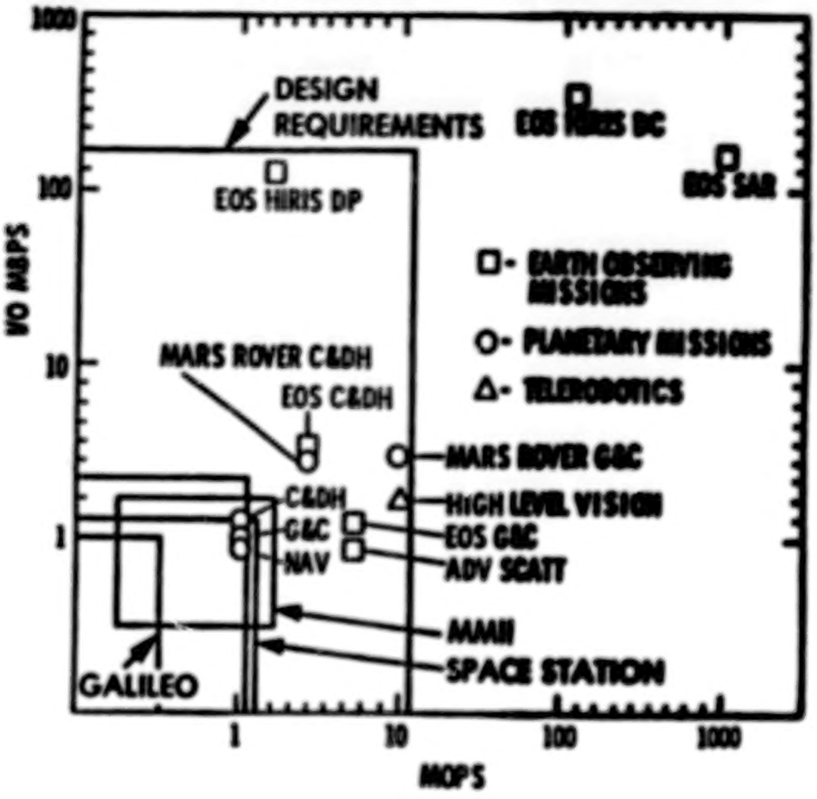
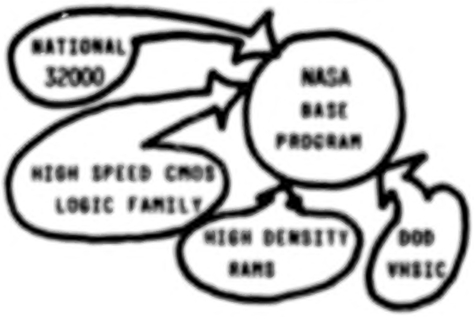


Figure 2.

DATA MANAGEMENT -- FLIGHT QUALIFIED COMPONENTS & COMPUTERS

SUBSYSTEM: DATA MANAGEMENT



PROBLEM: CURRENT FLIGHT QUALIFICATION PROGRAM LAGS TECHNOLOGY INSERTION BY 6 TO 10 YEARS.

OBJECTIVE: DEVELOP FAST COMPONENT TECHNOLOGY WHICH IS RADIATION & SEU INSENSITIVE AND FLIGHT QUALIFIED BY LATE 1990'S. REESTABLISH COMPONENT BASE PROGRAM TO FILL GAP.

APPROACH: CONTINUE TO FUND SANDIA FOR PRODUCTION OF 32000 NATIONAL PART SET. ADD ADDITIONAL HC PARTS. ADD ADDITIONAL FUNDS TO ESTABLISH FEASIBILITY TO TRANSITION FROM CMOS TO G_AA_S OR OTHER IN LATE 1990'S.

EXPECTED RESULTS: FAST PROCESSOR PART SET WHICH WILL PROVIDE COMPUTER BUILDING BLOCKS FOR SPACECRAFT 2000. REDUCED FEATURE SIZE AT 1 1/4 MICRONS (FROM VHSIC THRUST) PLUS G_AA_S OR OTHER SHOULD PROVIDE 5 MIP MICROPROCESSOR, RAD HARD TO >> 30.000 RADS (S_I) AND LET'S OF 37 K_R.

Figure 3.

DATA MANAGEMENT -- DATA STORAGE

PROBLEM: S/C 2000 REQUIRES $\geq 10^{12}$ BITS STORAGE AND RAPID ACCESS DATA BUFFERING; DEVICE SHOULD SUPPORT RATES FROM 10 MBPS TO 1 GBPS.

OBJECTIVE: DEVELOP LOW-POWER, WEIGHT MAGNETIC TAPE TECHNOLOGY FOR TERABIT RECORDER. BRING OPTICAL DISK DEVICE TECHNOLOGY ALONG FOR HIGH-SPEED BUFFER.

APPROACH: DEPEND ON CURRENT PROGRAM AT ODETICS FOR TAPE RECORDERS. AUGMENT TO REDUCE POWER AND WEIGHT. CONTINUE RCA SUPPORT TO OPTICAL DISK DEVICES: LOOK AT FLIGHT QUALIFICATION ISSUES.

EXPECTATIONS: SHOULD HAVE FLIGHT QUALIFIED STORAGE DEVICES FOR S/C 2000 WHICH CAN SUPPORT TERABIT STORAGE AND HIGH RATE BUFFERING.

Figure 4.

DATA MANAGEMENT -- SOFTWARE DEVELOPMENT TOOLS

PROBLEM: SPACECRAFT FLIGHT PROGRAMS IN THE YEAR 2000 WILL BE PROHIBITIVELY EXPENSIVE TO ENGINEER, DEVELOP, TEST AND MAINTAIN WITH THE SOFTWARE DEVELOPMENT TOOLS CURRENTLY IN USE.

OBJECTIVE: DEVELOP AN INTEGRATED SOFTWARE ENGINEERING AND DEVELOPMENT ENVIRONMENT ASSISTED BY EXPERT SYSTEM TECHNOLOGY FOR AIDING IN THE:

- GENERATION OF SOFTWARE REQUIREMENTS, DESIGN, CODE, TEST CASES, TEST PROCEDURES AND DOCUMENTATION.
- CONFIGURATION MANAGEMENT OF THE SOFTWARE.
- IDENTIFICATION OF DESIGN, CODE, TEST CASE AND DOCUMENTATION CHANGES DICTATED BY REQUIREMENTS CHANGES.
- LEARNING THE SOFTWARE SYSTEM (INTERACTIVE, USER-FRIENDLY ELECTRONIC "USER'S MANUAL").

APPROACH:

1. MONITOR THE DEVELOPMENT OF SUCH TOOLS BY SPACE STATION, SDI AND INDEPENDENT INDUSTRY INITIATIVES.
2. INITIATE NASA PROGRAMS FOR DEVELOPING SUCH TOOLS IF OTHER AGENCIES DO NOT.

EXPECTED RESULTS:

REDUCE SOFTWARE DEVELOPMENT AND MAINTENANCE COSTS BY AN ORDER OF MAGNITUDE.

D. BRADY

Figure 5.

DATA MANAGEMENT -- OPERATING SYSTEMS

PROBLEM: THE NEED EXISTS FOR A DISTRIBUTED OPERATING SYSTEM WHICH HELPS MANAGE SYSTEM FAULT TOLERANCE AND WHICH CAN ITSELF SWITCH IN AND OUT OF HIGHLY FAULT TOLERANT CONFIGURATIONS AS A FUNCTION OF SOME SOFTWARE OR SYSTEM CONDITION.

OBJECTIVE: DEVELOP AN OPERATING SYSTEM PORTABLE TO THE ON-BOARD COMPUTERS OF THE YEAR 2000 WHICH PROVIDES THE FACILITIES FOR

- RELIABLE INTERPROCESSOR COMMUNICATION
- SYNCHRONIZATION OF COMMUNICATING TASKS BOTH ON THE LOCAL PROCESSOR AND ON OTHER PROCESSORS IN THE SYSTEM
- SYSTEM UTILITIES TO ASSIST IN FAULT MANAGEMENT OF THE SYSTEM, PARTICULARLY RECOVERY FROM FAULTS IN COMMUNICATING PROCESSORS.
- SELECTABLE FAULT TOLERANCE MODES FROM MINIMAL FAULT TOLERANCE TO TRIPLICATION AND VOTING.

APPROACH:

1. DEFINE SPECIFIC FEATURES AND REQUIREMENTS FOR THE VARIOUS FAULT TOLERANCE MODES, INCLUDING METHODS FOR ACHIEVING SOFTWARE FAULT TOLERANCE.
2. DEFINE REQUIREMENTS FOR THE REMAINDER OF THE OPERATING SYSTEM.
3. SPONSOR THE DESIGN, DEVELOPMENT AND TESTING OF THIS OPERATING SYSTEM.

EXPECTED RESULTS:

SHOULD HAVE FAULT TOLERANT, DISTRIBUTED OPERATING SYSTEMS TO SUPPORT SINGLE OR MULTIPLE NODE COMPUTERS.

D. BRADY

Figure 6.

DATA MANAGEMENT -- LANGUAGES

PROBLEM: THE STANDARDIZATION ON ADA WITHIN DOD AND NASA LEAVES ON-BOARD SOFTWARE DEVELOPERS WITH SEVERAL CONCERNS:

- EFFICIENCY AND MATURITY OF THE COMPILER.
- SHORT COMINGS OF THE LANGUAGE FOR REAL-TIME CONTROL APPLICATIONS.
- SHORT COMINGS OF THE LANGUAGE FOR INTERPROCESS COMMUNICATION AND SYNCHRONIZATION.

OBJECTIVE: DEVELOP A HIGH-ORDER LANGUAGE (HOL) WHICH MORE EASILY MEETS THE REQUIREMENTS OF A REAL-TIME, INTERACTIVE DISTRIBUTED PROCESSING SYSTEM WITH A MATURE, EFFICIENT COMPILER BY THE YEAR 2000.

APPROACH:

1. FUND A STUDY TO TRADE THE VIABILITY OF EXTENDING ADA VERSUS STANDARDIZING ON SOME OTHER LANGUAGE WHICH IS MORE APPROPRIATE TO THIS APPLICATION.
2. IF ADA IS SELECTED, DEFINE A SET OF "STANDARD" EXTENSIONS TO THE LANGUAGE WHICH MEET OUR REQUIREMENTS.

EXPECTED RESULTS:

AN ADA VARIATION WHICH WILL STANDARDIZE SOFTWARE DEVELOPMENT FOR S/C 2000 AND BEYOND.

D. BRADY

Figure 7.

C-3

DATA MANAGEMENT -- FAULT TOLERANCE AND TESTING

PROBLEMS/NEEDS:

0 SIMPLER FAULT DETECTION. ISOLATION. AND RECOVERY TECHNIQUES WHICH RETAIN ADHERENCE TO FUNDAMENTAL REQUIREMENTS (EG. $P_F > 10^9$/HR: DATA CONGRUENCY. CORRELATED. TRANSIENT. BRIZANTINE FAILURES. ETC.)

0 FLEXIBLE CONNECTIVITY AND CONTROL FOR DISTRIBUTED. TIME CRITICAL. INTERACTIVE PROCESSING

0 TRUSTWORTHY SOFTWARE VIA "FAULT" TOLERANCE: PERHAPS EVENTUALLY VIA ERROR-FREE CODE

0 INTEGRATION OF SECURITY (EG. MARKOV) FOR EVALUATION. VERIFICATION. & MODIFICATION

0 EXTENSION OF TECHNIQUES TO NON-GENERAL PURPOSE ARCHITECTURES (MASSIVE PARALLEL. DATA FLOW)

0 INCORPORATION OF NEW COMPONENT TECHNOLOGIES (VHSIC $G_A A_S$. ETC.)

OBJECTIVE:

REDUCE RISK OF TECHNOLOGY SHORTFALL IF "COATTAILS" DON'T MATERIALIZE.

APPROACH:

MONITOR AND. IF/WHERE NECESSARY. AUGMENT ONGOING PROGRAMS (EG SDI) VIA SELECTED DEVELOPMENT AND GROUND-BASED TEST BED DEMONSTRATIONS.

EXPECTED RESULTS:

MATURE TECHNOLOGY BASE IN ALL AREAS ABOVE BY MID-LATE 90'S.

M. W. JOHNSTON 10/20/86

Figure 8.

DATA SYSTEMS -- FIBER OPTIC NETWORKS

PROBLEM: 500 MB FIBER OPTIC SPACECRAFT LOCAL AREA NETWORKS ARE NOT AVAILABLE TO SPACECRAFT SYSTEMS BECAUSE OF THE LACK OF SPACE QUALIFIED COMPONENTS.

OBJECTIVE: TO SPACE QUALIFY SEMICONDUCTOR LASER TRANSMITTERS. P-I-N RECEIVERS. ANALOG CONDITIONING AND STABILIZING CIRCUITRY. AND OPTICAL ELEMENTS NECESSARY TO IMPLEMENT SPACE QUALIFIED FIBER OPTIC LOCAL AREA NETWORKS (FOLAN) IN THE RANGE OF 300-500 MBT/SEC.

APPROACH: TO SPACE QUALIFY SINGLE MODE FIBER OPTIC CABLES. CONNECTORS.
TO SPACE QUALIFY LASER TRANSMITTERS. P-I-N RECEIVERS.
TO DEVELOP AND SPACE QUALIFY PACKETIZATION. AND PROTOCOL DECISION MAKING LOGIC.

EXPECTED RESULTS:

COMPONENT TECHNOLOGY BASE TO ASSURE 300-500 MBPS LOW ERROR RATE FOLAN'S FOR SPACECRAFT.

Figure 9.

DATA MANAGEMENT -- COMMUNICATION PROTOCOLS

PROBLEM: SUCCESSFUL INSERTION OF PACKET-SWITCHING TECHNOLOGY INTO SC-2000.

OBJECTIVE: REPLACE A MAJORITY OF SPECIAL CABLING IN SPACECRAFT WITH A PACKET-SWITCHED, SHARED COMMUNICATION MEDIUM (PROBABLY FIBER OPTICAL LOCAL-AREA-NETWORK BASED). MOST POINT-TO-POINT CABLES WOULD BE REPLACED BY A TAP INTO THE MEDIUM.

ISSUES: THIS TECHNOLOGY IS BEING DEVELOPED PIECEMEAL TODAY IN MANY LOCATIONS. HOWEVER, THE CONSTRAINTS FACED IN SC-2000 ARE NOT ADDRESSED BY EXISTING PROGRAMS. THE SC-2000 CONSTRAINTS/REQUIREMENTS INCLUDE:

- o REAL-TIME GUARANTEED RESPONSE
- o PRIORITY FOR CRITICAL COMMUNICATIONS
- o SUBSUMING (ALMOST) ALL POINT-POINT COMMUNICATIONS ON THE SPACECRAFT
- o RELIABLE COMMUNICATIONS (WELL BEYOND THE BIT ERROR RATE OF THE COMM. MEDIUM)
- o VERY HIGH BANDWIDTH
  - o SINGLE INSTRUMENTS 100-300 MBAUD
- o REPLACING TDM FOR MOST USAGES

- ● WHILE NO CONSTRAINT ABOVE IS PROHIBITIVE, THE SIMULTANEOUS SOLUTION OF ALL OF THEM IS BEYOND CURRENT TECHNOLOGY.

Figure 10a.

DATA MANAGEMENT -- COMMUNICATION PROTOCOLS (CONTINUED)

- ● CURRENT LINK-LEVEL PROTOCOLS CANNOT HANDLE 100-300 MBAUD IF IMPLEMENTED IN SOFTWARE, AND ARE TOO COMPLEX TO IMPLEMENT IN HARDWARE. NEW PROTOCOL(S) ARE NEEDED.
- o THE ABOVE IS EVEN MORE TRUE OF TRANSPORT-LEVEL PROTOCOLS, WHICH ARE FAR TOO SLOW. A NEW PROTOCOL IS NEEDED HERE, TOO.

APPROACH: NASA SHOULD FUND A SC-2000 BRASSBOARD IMPLEMENTATION, SOLVING ALL THE ABOVE CONSTRAINTS SIMULTANEOUSLY IN A SYSTEM WHICH CAN BE THE TEST BED OR PROTOTYPE FOR THE PROTOCOLS, CHIPS, COMMUNICATION MEDIUM, OPERATING SYSTEM, FAULT DETECTION/RECOVERY, ETC.

EXPECTED RESULT:

THE OUTPUT INCLUDES:

- o NEW PROTOCOLS
- o NEW COMM. CHIPS
- o WORKABLE ALGORITHMS AND STRATEGIES FOR FAULT TOLERANCE
- o WORKING OPERATING SYSTEM SOFTWARE

WITHOUT THE EARLY AVAILABILITY OF THIS TECHNOLOGY, SPECIAL INTERESTS WITH SPECIAL NEEDS WILL FORCE MULTIPLE NON-STANDARD INTERFACES INTO SC-2000, DUE TO THEIR OWN NEED FOR EARLY DESIGN FREEZES. THIS WILL MAKE THE NECESSARY COMMONALITY OF INTERFACE AND OF STANDARDIZATION IMPOSSIBLE.

Figure 10b.

DATA MANAGEMENT -- SECURITY

PROBLEM: SC 2000 WILL HAVE TO SUPPORT A WIDE RANGE OF USERS, MANY OF WHICH WILL HAVE STRINGENT DATA SECURITY REQUIREMENTS. THESE REQUIREMENTS CANNOT BE MET BY PRESENT SYSTEMS.

OBJECTIVE: IDENTIFY SC 2000 SECURITY REQUIREMENTS IN DETAIL. PRODUCE A FORMAL SECURITY POLICY. INSURE THAT THE NEEDED SECURITY TECHNOLOGY IS AVAILABLE AND IS UTILIZED DURING THE SYSTEM DEFINITION PHASE.

APPROACH: NASA SHOULD BEGIN INTERACTIONS WITH THE NATIONAL SECURITY AGENCY AND THE NATIONAL COMPUTER SECURITY CENTER TO IDENTIFY NASA'S NEEDS IN SEVERAL AREAS:

-- SOFTWARE SECURITY (ESP. COMM & OPERATING SYS.)
-- COMMUNICATIONS SECURITY
-- OPERATIONS AND DEVELOPMENT INTEGRITY ASSURANCE

EXPECTED RESULTS:

SECURITY ISSUE IS INCORPORATED DURING EARLY DEVELOPMENTS OF PROTOCOLS AND OPERATING SYSTEMS.

-- IF NOT BEGUN NOW, SECURITY IS HARDER (OR IMPOSSIBLE) TO ADD LATER.
-- SECURITY & FAULT TOLERANCE MAY BE COMPLEMENTARY (EG, CRYPTOGRAPHIC CHECKSUMS MIGHT AUGMENT OR REPLACE OTHER ERROR DETECTION CODES, WITH ADDED VALUE FROM RESULTING INTEGRITY CHECKS).

Figure 11.

DATA MANAGEMENT -- TECHNOLOGY EVOLVABILITY BY TRANSPARENCY

1. PROBLEM: SUBSYSTEM HIERARCHICAL MODELS NEED TO BE EXERCISED IN A SYSTEM WIDE MODELLING TOOL. MODELLING RESULTS MUST BE VALIDATED IN A TEST BED PRIOR TO SUBSYSTEM INTERFACE/PROCESSOR-MEMORY-SOFTWARE PARTITIONING. HEURISTIC METHODS CURRENTLY IN USE CAUSE OVERDESIGN/UNDERDESIGN PROBLEMS AT SUBSYSTEM INTEGRATION. SYSTEMS MUST BE COMPLETELY REDESIGNED TO ACCOMMODATE TECHNOLOGY UPGRADES.
2. OBJECTIVE: SIGNIFICANT ARCHITECTURAL MODELLING TOOLS AND METHODOLOGY NEED DEVELOPMENT. PARTICULAR MODELS NEED TO BE DEVELOPED FOR PROCESSOR, STORAGE AND SOFTWARE. TEST BED DEVELOPMENTS MUST BE INITIATED TO MEASURE MODEL PARAMETERS AND VALIDATE END TO END MODELS.
3. APPROACH:
   - SELECTION OF METHODOLOGIES/HIERARCHICAL TOOLS
   - DEVELOP TOOL - MODEL ELEMENTS
   - ACQUIRE TEST BED ELEMENTS
   - INTEGRATE WITH OTHER SUBSYSTEMS & SUBSYSTEM MODELS
   - ITERATE SYSTEM CONFIGURATIONS/TOPOLOGIES TO GIVE VALIDATED DESIGNS
4. EXPECTED RESULTS:
   - FIRM PLANNING SYSTEM/SUBSYSTEM INTERFACE DEFINITIONS
   - SPECIFICATIONS FOR SUBSYSTEM DEVELOPMENTS
   - SYSTEM DESIGN MODELLED AND VALIDATED

Figure 12.

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PROPULSION WORKING GROUP REPORT

James Mavrogenis, Chairman
Hughes Aircraft Company

James Kelley, Cochairman
Jet Propulsion Laboratory

James Stone, Cochairman
NASA Lewis Research Center

POSITION STATEMENT

As high payoff propulsion technologies for application in the year 2000 and beyond were identified, it became obvious that many of them had been initially worked on in the 1960's and 1970's. In most cases their development was halted not by technological impasses but by the lack of funding, driven in part we believe, by a short term payoff mind-set within the decision-making establishments in Government. Although the high payoffs of these technologies were obvious to industry, the high development costs, the associated risks, and the absence of an immediate application precluded private development. No national policy existed or currently exists that recognizes the Government's responsibility to fund the constant and steady development of technology as a national resource. The technology being researched and developed for the SDI could be cited as an attempt to provide such as policy, but it falls far short of the mark for many reasons including being tied to a specific application.

We believe that the greatest benefit that could come from the Spacecraft 2000 initiative would be the realization at the highest levels of Government of the real losses the country has sustained in space leadership because of the short term mentality that has controlled the development of high payoff space technologies. The Spacecraft 2000 steering committee should assume a leadership role in bringing this message to the Congress. It should then assist in the definition and establishment of a long term technology development program.

POSITION STATEMENT

MANY ADVANCED PROPULSION TECHNOLOGIES HAVE BEEN DEMONSTRATED OVER THE LAST 20 YEARS. FRAGMENTED FUNDING AND A LACK OF AWARENESS OF THE HIGH PAYOFFS HAVE KEPT THE TECHNOLOGY FROM BEING DEVELOPED. DEVELOPMENT COSTS AND RISKS PRECLUDE PRIVATE FUNDING OF THESE TECHNOLOGIES.

SELECTION CRITERIA

It is obvious that not all the propulsion technologies that are identified in this briefing can or should be developed for application by the 21st century. The four selection criteria identified here have been chosen so that the technologies with the highest payoff - a term whose definition is mission dependent - can be identified for continued development. Also mission dependent is the weight that each criteria should carry in an evaluation. Weighting the criteria was beyond the scope of the working group meeting but should be addressed in a subsequent working group meeting.

This working group believes that technologies should be developed as a national resource. As such, the use of the term "mission" above implies not a specific spacecraft mission but a national space policy. By way of example, if our national goal was the manned exploration of the planets, then propulsion technologies which offered the shortest trip time should be selected. These same technologies would most likely be unsuitable if our national space goal was development of the space station's capabilities.

Technologies which reduce the dry weight of a propulsion system or which deliver a greater specific impulse (performance) from each pound of system loaded weight offer the highest payoff. Except for manned missions this criteria should carry the greatest weight in the selection evaluation. System reliability and safety enhancing technologies should carry the greatest weight for manned missions. The last two criteria, cost and risk, refer to the development of each technology. With limited resources it is imperative that the benefit promised by each technology be weighed against the cost and risk of successfully bringing forth a mature capability. We must also recognize that any such assessment is highly subjective and will sometimes result in technology development false starts and program deadends.

PROPULSION-SPECIFIC TECHNOLOGY

SELECTION CRITERIA

- PERFORMANCE
    - HIGHER MASS FRACTION/I_{SP}
- RELIABILITY & SAFETY
- COST
- RISK

EXISTING TECHNOLOGY LIMITS

This chart illustrates the payoff from a modest 20% improvement in specific impulse. Technologies exist, e.g. ion propulsion which offer a 1000% improvement in specific impulse resulting in nearly a five fold increase in payload weight delivered to geosync orbit by the shuttle if such a system was used to propel the transfer vehicle. The sad truth is that while the U.S. debates the development of giant rockets capable of boosting the enormous SDIO weights into orbit, ion propulsion systems which could eliminate the need for giant new boosters have been demonstrated in space and yet remain unapplied.

EXISTING TECHNOLOGY LIMITS & PERFORMANCE

- o 20% TYPICAL PERFORMANCE IMPROVEMENT IN SPECIFIC IMPULSE GIVES HIGH PAYOFF.

GEOSYNC EXAMPLE

- o 100% GREATER PAYLOAD CAPABILITY

	@ EXISTING I_{SP} 200-300 SEC	@ I_{SP} INCREASED 20%
PAYLOAD MASS	500 LBS	1,000 LBS
SPACECRAFT (BUS)	1,500	1,500
DRY	2,000	2,500
7 YR GEO PROPELLANT	600	600
BEGIN GEO	2,600	3,100
APOGEE PROPELLANT	2,600	2,500
GTO	5,200	5,600
PERIGEE PROPELLANT	5,200	4,500
LEO	10,400	10,100
TOTAL PROPELLANT MASS	8,400 LBS	7,600 LBS

KEY TECHNICAL PROBLEMS IN CURRENT S/C PROPULSION

- AT LIMITS OF CURRENT PROPELLANT PERFORMANCE
- APPROACHING MATERIAL LIMITS
    - PERFORMANCE
    - LIFE
    - PROCESSES
- FEED SYSTEM DESIGN
    - HEAVY
    - PROPELLANT GAGING ACCURACY
- LACK OF STANDARDIZATION
- LACK OF SPACE SERVICEABILITY
- PLUME PROBLEMS
    - IMPINGEMENT
    - CONTAMINATION

NEAR-TERM RECOMMENDATIONS - HIGH PAYOFF TECHNOLOGIES

The high payoff technologies identified should be pursued in the near term, but funding realities make it unlikely that all could be pursued simultaneously at significant levels. Therefore, studies should be undertaken to quantify the benefits of these technologies to a wide range of missions. The results of these studies, along with a projection of the time frame when the technology is required for each major type of mission, should allow the planning of a technology development and demonstration program resulting in the greatest payoff within the resources provided.

HIGH PAYOFF TECHNOLOGIES

- ADVANCED BIPROPELLANT SYSTEMS
- ELECTRIC PROPULSION SYSTEMS
- PROPELLANT FEED SYSTEM TECHNOLOGIES
- THESE TECHNOLOGIES HAVE DEMONSTRATED FEASIBILITY.
  CONSTANT GOVERNMENT FUNDING IS REQUIRED TO BRING THEM
  TO A TECHNOLOGY READINESS STATE.
- PRIORITIZATION IS DRIVEN BY MISSION MODEL.

PROPULSION TECHNOLOGIES

A number of technologies and related issues which should be addressed were identified. Those thought to have the highest potential payoff, which will be discussed in more detail, are the following:

Advanced Bipropellant Systems
Electric Propulsion Systems

A high payoff is also expected from

Advanced Materials
Standardization
An In-Space Test Bed

In addition to these, there are several other areas which should not be neglected. Plume modeling is needed to allow prediction of the interaction of the thruster exhaust with the spacecraft, particularly for payloads where contamination is an issue. Valid data and models do not presently exist for plumes from small rockets. Verification of such models is a major justification for the In-Space Testbed. The ability of refuel and service propulsion systems is space should be considered, even though it may pay off only for a few specific cases. The development of automated, expert system design aids would be a cost saver. The manufacture of propellants in space could open new option; of particular interest is the electrolysis of water to produce H_2 and O_2. The analysis of potential payoffs for all of these technologies should be a part of the program planning process and should be updated as the program progresses.

PROPULSION TECHNOLOGIES

- ADVANCED BIPROPELLANT SYSTEMS
- ELECTRIC PROPULSION SYSTEMS
- PROPELLANT FEED SYSTEM TECHNOLOGIES
- ADVANCED MATERIALS
- STANDARDIZATION

PLUME MODELING

- IN-SPACE TEST BED

ABILITY TO SERVICE IN SPACE
AUTOMATED DESIGN
SPACE MANUFACTURING OF PROPELLANTS
ANALYSIS OF PAYOFFS FOR EACH TECHNOLOGY AS PART OF
THE PROGRAM PLANNING PROCESS

---

* INDICATES FURTHER DETAIL IN FOLLOWING CHARTS.

ADVANCED BIPROPELLANT SYSTEMS

Advanced bipropellant systems offer payoffs to a wide range of missions. A number of potential high-energy propellant combinations, such as N_2O_4/N_2H_4, CIF_5/N_2H_4 (or blends), and F_2/N_2H_4, should be evaluated and the most promising selected for advanced development. All of these propellant combinations have greater performance than present N_2O_4/MMH systems and all have been ground tested. In addition, in each of these cases, hydrazine is the fuel and could be used as a monopropellant for attitude control. The propellant combinations are listed in increasing order of I_{sp} and increasing order of technical difficulty. N_2O_4/N_2H_4 is state of the art but a system to use it in spacecraft has not been developed. The CIF_2 system is not cryogenic; the F_2 system is, but has the highest performance of the group.

High temperature thruster materials, including rhenium, composites and ceramics should be investigated to allow the minimization of cooling flows, thereby increasing performance, while offering very large increases in lifetime.

ADVANCED BIPROPELLANT SYSTEMS

- EVALUATE HIGH-ENERGY BIPROPELLANTS -- SELECT FOR ADVANCED DEVELOPMENT, EG:
  - N_2O_4/N_2H_4
  - CLF_5/N_2H_4 OR HYDRAZINE BLENDS
  - F_2/N_2H_4
- EVALUATE ADVANCED ENGINES & MATERIALS; EG:
  - RHENIUM
  - COMPOSITES
  - CERAMICS

ELECTRIC PROPULSION SYSTEMS

Several electric propulsion systems offer major performance break-throughs for low thrust applications (Figs. 1,2).

Xenon Ion System:

Ion propulsion offers the highest specific impulse available by the year 2000. Ion engines have been tested successfully in space using metal vapor propellants. In order to be applicable to many missions it will be necessary to demonstrate performance in space with inert gas propellants, such as xenon.

Arcjet Systems:

Arcjet systems offer major payoffs both for station keeping (Fig 3) and orbit transfer applications.

Low-power arcjets represent the next logical step in hydrazine propulsion beyond current state-of-art resistojets. (Fig 4) Laboratory testing has established the feasibility of such a system at the appropriate thrust and power levels. Further ground testing is needed to optimize the system and to establish performance/lifetime trades. In-space testing will be required to address critical integration issues such as plume effects and EMI.

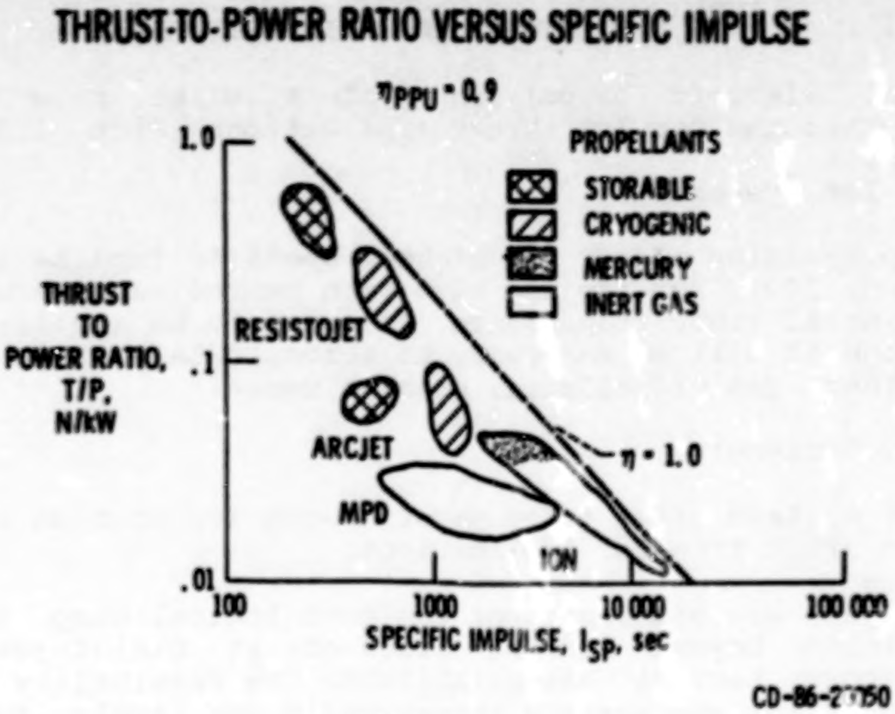
High-power arcjets using ammonia propellant and, in the future, hydrogen, are promising for orbit transfer.

Higher Thrust Pulsed Plasma Thrusters:

Pulsed plasma thrusters are used in applications where very precise impulse bits are required.

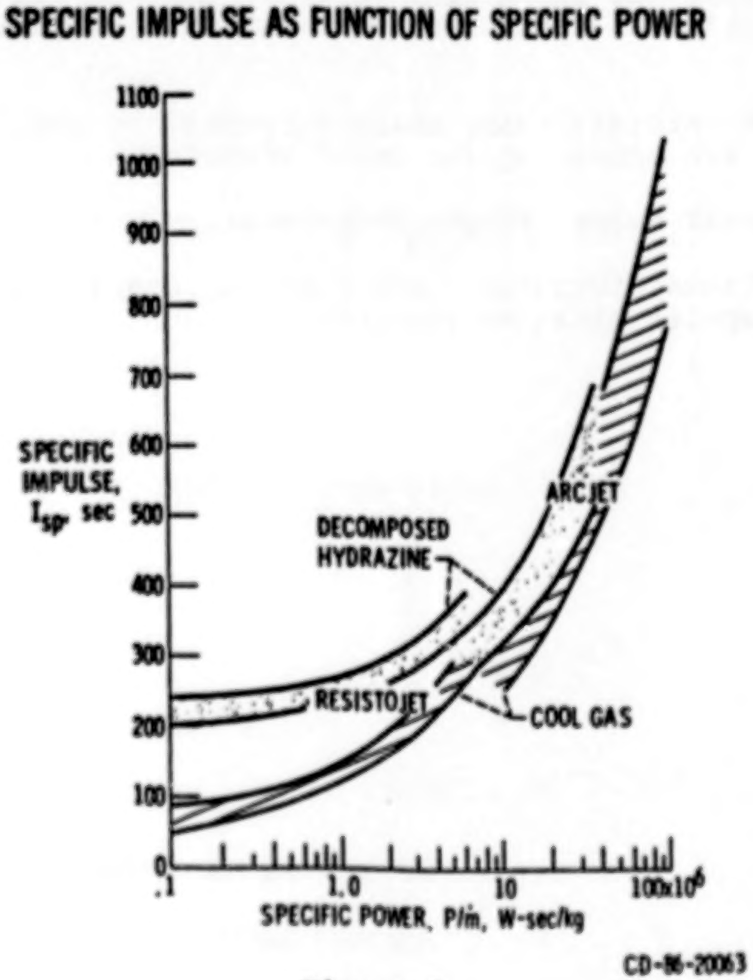
ELECTRIC PROPULSION SYSTEMS

- XENON ION SYSTEM
- ARC JET SYSTEMS
    - LOW POWER (STATION KEEPING)
    - HIGH POWER (ORBIT TRANSFER)
- HIGHER THRUST PULSED PLASMA THRUSTORS



THRUST-TO-POWER RATIO VERSUS SPECIFIC IMPULSE

Figure 1.



SPECIFIC IMPULSE AS FUNCTION OF SPECIFIC POWER

Figure 2.

ARCJET AUXILIARY PROPULSION

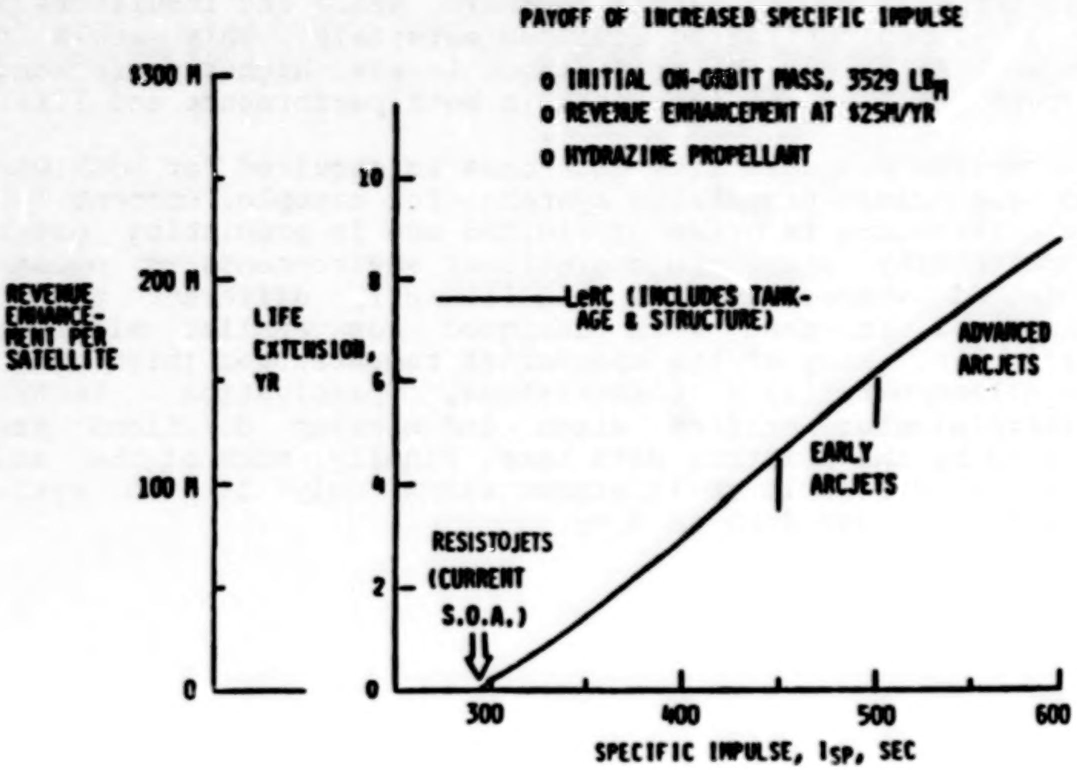


Figure 3.

EVOLUTION OF HYDRAZINE ELECTROTHERMAL AUXILIARY PROPULSION

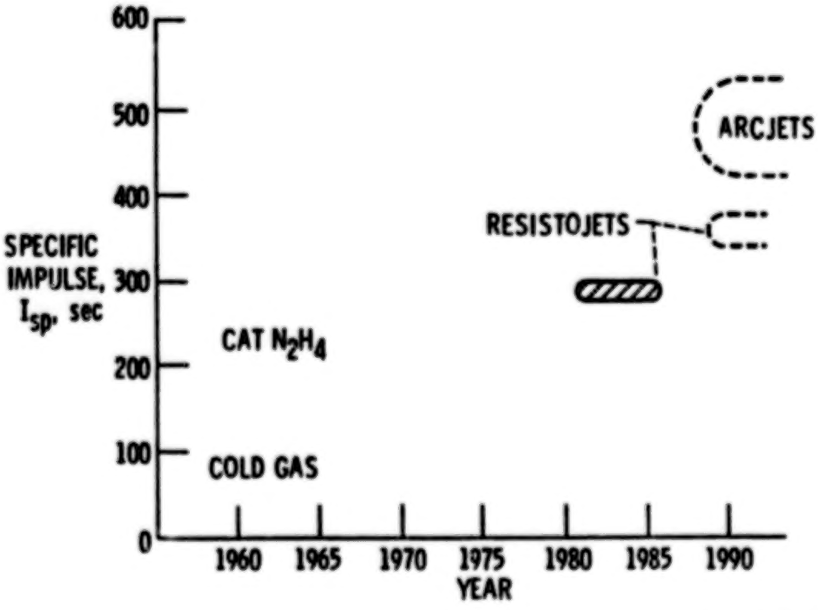


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Figure 4.

MATERIALS

High-temperature, long-life chambers, seals and insulators should be developed utilizing advanced materials. This would permit longer life at current performance levels. higher performance at current lifetime, or increases in both performance and life.

A materials compatibility data base is required for both chemical and electrical propulsion systems. For example, current data in the literature is often of limited use in predicting materials compatibility since the operational environments in present or projected spacecraft are significantly different than those considered in past work designed for earlier missions. In particular, many of the spacecraft temperatures (high and low), propellant/material combinations, passivation techniques, filter/injector orifice sizes and mission durations are not covered by the existing data base. Finally, much of the existing data is difficult to interpret since only limited systematic testing has been done to date.

MATERIALS

- o DEVELOP HIGH-TEMPERATURE, LONG-LIFE CHAMBERS, SEALS AND INSULATORS
    - CERAMICS
    - ELASTOMERS
    - METALLICS
- o DEVELOP MATERIALS COMPATIBILITY DATA BASE
    - PROPELLANTS
    - EXHAUST PRODUCTS

PROPELLANT FEED SYSTEM TECHNOLOGY

- PUMPS
- LIGHT WEIGHT TANKS
- IMPROVED PLUMBING
  - FLEXIBLE JOINTS/LINES
  - ZERO LEAK DISCONNECTS
- IMPROVED VALVES
  - LEAKAGE, LIFE, WEIGHT
  - REMOTE CONTROL FILL VALVES
- INCREASED ACCURACY INSTRUMENTATION/ CONTROL SYSTEMS
- BETTER UNDERSTANDING OF PMDS

ROCKET EXHAUST PLUME MODELS/DATA

It is often said that experiment s are needed to validate plume/contamination analysis codes. Such validation tests generally evolve into end-to-end measurements such as deposition on a QCM. The final results are like "X mg/cm^2 of deposit was collected after N_1 firings of N_2 sec. total duration". Occasionally, the deposit will be identified as having a given rate of desorption or qualitative measurements of composition (e.g. "contained nitrates") will be given. State-of-art plume codes will not accurately predict these results and may not even be designed to do so.

The cause of any discrepancies between predictions and such end-to-end measurements cannot be determined from the measurements themselves. This is because (especially as related to contamination from biprops) the error could be in any of three areas:

1) **Prediction of composition at the exit plane, where state of art codes ignore mixing rates, use empirical correlations (i.e. atomization parameters) beyond their range of validity, and require thermochemical data that has never been measured.**

2) **Plume transport phenomena, where (except for DSMC calculations) species separation and other rarefaction effects are ignored.**

3) Capture and chemical interactions of plume species on spacecraft surfaces, which is a virtually virgin field. Modules in CONTAM which purport to deal with this talk of equilibrium reactions and other assumptions that cannot be justified by existing observations: (in equilibrium diamonds turn to graphite and no containment would persist forever in a vacuum).

The motivation for space-based experiments is that the plume transport cannot be accurately modeled in ground-based vacuum chambers. Paradoxically, this is the best understood area of the three. Work that is more valuable would determine what assumptions are valid for, and thermophysical properties that are needed to analyze, the first and third areas. These could take the form of:

1) Tomographic transmission spectroscopy or other techniques to find exit plane composition.

2) High time-resolution measurements of exit plane properties and intermittancy to study mixing effects.

3) Molecular beam studies of molecular sticking and chemical reactions as a function of:

   a) impingement velocity (1 --> 5 km/s)
   b) substrate (crystal planes --> thermal control point)
   c) incidence angle
   d) beam intensity
   e) substrate temperature
   f) etc.

4) Determination of impacts of low (non-zero) cont. levels on instruments.

With this sort of program, NASA, DoD and industry could start to define requirements and input data for codes that could be expected to pass validation (i.e. end-to-end) tests.

STANDARDIZATION

Standardization of documentation, although not a technology, when correctly applied can save funds that could be better spent in technology development. With respect to hardware, the intent is to standardize on the size of items such as valves, regulators, and possibly thrust levels for small control engines. There is no intent to suggest that components be built for stock since this would be very costly and discourage progress in propulsion technology.

STANDARDIZATION

- * o SAFETY FACTORS
- * o TEST REQUIREMENTS
- o FRACTURE MECHANICS
- o CONTAMINATION MODELS
- * o TEST PROCEDURES
- o PROPULSION COMPONENTS

  IE REGULATORS, VALVES, THRUSTER SIZE
- * o DOCUMENTATION

  EMPHASIZE REDUCTION

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* GOVERNMENT/INDUSTRY WORKING GROUP - COST SAVINGS

IN-SPACE TEST BED

Some of the new technology cannot be validated in ground test but instead requires space-based testing. Technologies such as plume/contamination model validation, analyses of ion and arcjet propulsion interaction with the spacecraft and propellant gaging concepts tested in a zero-gravity environment all require a space-based platform. What is envisioned is a simple spacecraft deployed from the shuttle and retrieved on a subsequent flight. The important characteristics for such a vehicle are identified in the chart. The most important of these is early availability. For technologies to be available by the year 2000, testing needs to be accomplished before 1995 to allow time for development, retest and qualification.

IN-SPACE TESTBED

- o DESIRED CHARACTERISTICS
  - EARLY 1990's AVAILABILITY
  - MODULAR POWER (MULTI-KW)
  - REUSABLE OR RETURNABLE
  - DURATION OF A FEW MONTHS
  - EMI MEASUREMENTS
  - ZERO SELF-CONTAMINATION
  - ACCURATE MEASURE OF IMPULSE

POST-2000 TECHNOLOGIES

The technologies discussed so far are all evolutionary in nature. While they will in many cases, e.g. ion propulsion, provide substantial improvements over current designs the truly dramatic improvements will come from the technologies listed in the chard. These technologies should be evaluated against a background of current knowledge to determine which ones warrant a low level of development effort now and which of these, lacking the necessary supporting technologies can be set aside for review in 5 years. Of those listed, a magneto plasma dynamic thruster appears to have the lead in earliest development.

POST-2000 PROPULSION TECHNOLOGIES
(REVOLUTIONARY CONCEPTS)

THERE ARE A NUMBER OF REVOLUTIONARY (AS OPPOSED TO EVOLUTIONARY) TECHNOLOGIES THAT SHOULD BE PURSUED IN THE 1986-2000 TIME FRAME. THESE TECHNOLOGIES WILL PROBABLY NOT BE READY IN 2000, BUT WORK NEEDS TO BE INITIATED NOW SO THE TECHNOLOGY WILL BE READY WHEN ITS NEEDED.

MAGNETO-PLASMA DYNAMIC THRUSTERS
MICROWAVE PROPULSION
SOLAR SAILS
SOLAR-THERMAL THRUSTERS
LASER PROPULSION
NUCLEAR FUSSION PROPULSION
HIGH ENERGY METASTABLE PROPELLANTS (H_4, ETC)
ANTI-MATTER PROPULSION

RECOMMENDATIONS FOR THE GOVERNMENT/INDUSTRY RELATIONS GROUP

- TO BE USED NEW TECHNOLOGIES NEED TO BE BROUGHT THROUGH FULL SCALE DEVELOPMENT BY THE GOVERNMENT
- STANDARDIZATION
  - SAFETY FACTOR
  - TEST REQUIREMENTS/PROCEDURES
  - SPECIFICATIONS
- DOCUMENTATION REDUCTION

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ATTITUDE CONTROL WORKING GROUP REPORT

Daniel Reid, Chairman
General Electric Company

Phillip Studer, Cochairman
NASA Goddard Space Flight Center

1.0 INTRODUCTION

The Spacecraft 2000 Workshop was held at the Hollenden House in Cleveland, Ohio, on July 29-31, 1986. Dr. J. Stuart Fordyce, of NASA Lewis Research Center, served as the conference chairman. The workshop objectives were a) to identify the critical needs and technologies for spacecraft of the 21st century and b) to recommend technology development and validation programs.

The workshop was accomplished by forming a number of technology working groups. This report documents the activities of the Attitude Control group. The group was chaired by Dan Reid (GE) and co-chaired by Phil Studer (NASA GSFC). The major participants were John Sesak (LMSC), Bob Williamson (Aerospace Corp.), Charles Gartrell (General Research Corp.), Bill Isely (HI), Cliff Swanson (Singer), and George Stocking (Sperry).

The ACS working group used the following approach to satisfy the workshop objectives:

- Establish the ACS requirements expected in the year 2000. These were based upon all missions, military and civil, for LEO and GEO. The group used a roundtable discussion to predict what the control needs would be in the 21st century.
- Establish the constraints which were likely to be placed upon the ACS of the year 2000. These were established to be sure that real world considerations influenced the group's conclusions.

- Predict the ACS technology state-of-the-art likely in the year 2000. This was a projection of where the technology would most likely be, without any extraordinary R&D effort, business-as-usual.
- Develop the expected ACS technology shortfalls based upon the expected requirements and the predicted technology state-of-the-art.
- Identify the critical ACS technology issues, where critical was defined as enabling. All of the identified shortfalls were discussed in detail. The critical were separated from the enhancing and desirable, and grouped into four related categories.
- Develop recommended ACS technology programs to address the critical issues. Four programs covering the critical issues were developed. For each recommended program an objective, rationale/need, approach/methodology, and payoff were established.

2.0 SUMMARY OF RESULTS

It was the consensus of the ACS working group that critical technology issues will have to be solved, if we are to satisfy the requirements of spacecraft in the year 2000. Critical technologies were identified in ACS sensors, processing, actuators, and test. Four programs were defined which would address all of the critical issues.

The ACS working group recommends that development programs be established as follows:

- ACS Validaton & Test - a ground and space-based test facility addressing both ACS hardware and software.
- Flexible Structure Control - concerning both dynamic and form control involving the sensors, the actuators, the algorithms, and design tools/techniques.
- ACS Autonomy - covering both navigation and operations with an

emphasis on fault detection and correction.

- ACS Sensors - addressing low noise, high accuracy devices which could be made applicable to future ACS designs.

The working group is aware of technology programs being conducted at various government agencies addressing some parts of these recommended programs. In most cases, the technology activity is limited to mission particular issues and promising approaches for some missions are rejected when not applicable to the sponsor's mission. Often the results of such R&D receives limited distribution, and the entire community cannot benefit from the activity.

It is recommended that the detailed planning of these programs consider all of the other planned R&D, and attempt to serve as a focus or integrating function of related activity.

Appendix A is the charts used at the workshop for the ACS working group final briefing. Appendix B presents the ACS working group members' mailing addresses.

3.0 ACS REQUIREMENTS - 2000

Spacecraft Attitude Control Systems in the year 2000 will have to be capable of satisfying the following requirements:

Increased Bandwidth -- is driven by the higher performance requirements of precision pointing applications as well as by agile/dynamic applications; the bandwidth required ranges up to 100 Hz. Large, flexible structures also require higher bandwidths than those presently used.

Micro-g Performance -- Accelerations in orbit are very low. Performance under, and measurement of, micro-g accelerations are required for precision pointing and stationkeeping applications. Some payloads, such as material processing, also require precise orientation and very low acceleration errors.

Modular -- Modularity is seen as the cost-effective approach to making modifications in a basic design in order to meet mission peculiar requirements.

Replaceable -- The capability of replacing entire functions with the spacecraft on station, in orbit; an example was the replacement of the ACS module on the Solar Max Mission spacecraft.

Serviceable -- Operating from the Space Shuttle or in the Space Station, replacement should be possible at lower levels, i.e., elements within a function, cleaning, refueling.

High Accuracy -- SDI missions push the state of the art in precision pointing. Future scientific missions also require very low jitter.

Fault Tolerant -- The ability to reconstitute the system, thus surviving and/or relieving ground station support.

High Reliability -- is necessary to protect the investment in a spacecraft system. Higher levels of reliability are driven by longer life.

Long Life -- 7 to 10 year life requirements are common today. Growth to a 10 to 15 year capability is necessary for many applications, with 30 years the goal for the Space Station; maintenance is permitted in the latter case.

Torque/Momentum Growth Capability -- To accommodate abrupt configuration changes. The configuration of large spacecraft (size and shape) will change significantly during construction, as various vehicles dock, and as appendages are added or removed. This will allow the use of large, lightweight structures and provide stable control of evolving structures.

Multiple Payload Pointing -- Precision pointing of multiple payloads on a large, flexible structure, expected in 2000, requires alignment transfer and stabilization techniques not now available.

Minimum Weight -- Weight drives launch costs directly. Minimizing weight also implies decreasing volume and improving handling capability.

Autonomy -- reduces upon ground support and maximizes the mission return. This involves health check (fault detection and correction) and maintenance (recalibration) in the context of limited ground station availability. Autonomous navigation is required to passively (without outside assistance) evade threats, thus improving survivability.

Robust -- The capability to handle dynamic conditions markedly different from the design requirements, i.e., the unexpected environment.

Adaptive -- Design in the ability to handle a variety of scenarios, i.e., all the expected.

Maneuverable/Agile -- Rapid retargetting is a requirement particularly of the SDI scenarios. Evasive maneuvers are seen as a common requirement for all high value/high priority future spacecraft.

Low Jitter -- is necessary to achieve low smear on imaging systems, optical communications links, and to concentrate the energy of weapons systems.

Payload Sensor Control Capability -- The ability to use the payload's sensors to control the spacecraft can reduce the mission cost and/or provide redundancy or the ability to reconfigure in the event of failure (robust).

SEU/Radiation Transient Immunity -- SEU immunity is necessary to avoid losing memory or the need to reload memory in regions where cosmic rays are plentiful. Transient immunity is necessary to operate through and/or survive a nuclear event.

4.0 ACS CONSTRAINTS - 2000

There will be significant constraints placed upon the spacecraft Attitude Control Systems in the year 2000. These constraints can be categorized at the component level and the subsystem level:

Component Constraints:

Low Cost -- components must be used in order to provide affordable redundancy.

Non-optimal -- components must be used which can satisfy the general needs of many different systems and configurations.

Demonstrated/Qualified -- components will have to be used to avoid any mission risk.

Limited Fields of View -- will be afforded to the attitude sensors because of the large structures and the payload priorities.

Subsystem Constraints:

Large Flexible Structures -- will be a major limiting factor for the subsystem. Not only will low frequency, undamped appendages exist on most spacecraft, but flexible structure will connect the ACS components and the payloads requiring control.

Variable Mass Properties -- of the spacecraft due to both expendable usage over long life and reconfiguration.

Limited Preflight Testing -- will be available because of the ACS hardware and software complexity, because of the test facility limitations, and because in some cases the hardware will already be on-orbit.

Alignment Transfers -- both to initialize payloads and filters and to correct for flexible structure will be needed for the ACS in 2000.

Distributed Components -- will constrain the subsystem. This will be necessary to accommodate payload requirements, to control large flexible structures, and provide serviceable configurations.

Radiator Pointing -- limitations will constrain not only the spacecraft attitude but also the allowable maneuvering. These large radiators will be needed to dump the heat generated on the anticipated high power spacecraft and will have to be pointed toward cold space at all times.

Uncompensated Momentum -- from articulated payloads, servicing, fluid transfer loops, and other moving mechanisms will have to be absorbed by the ACS.

Crew Safety -- for manned launches, manned servicing, or manned missions will constrain the ACS designs in 2000.

5.0 PREDICTED ACS TECHNOLOGY - 2000

The state-of-the-art in Attitude Control Systems technology is predicted to be as follows, assuming that only normal R&D is performed:

Multimode/Reprogrammable -- Generic ACS systems will be applied to a number of systems/missions. Configuration for a particular requirement will be realized by S/W reprogramming.

Self-Alignment -- Prior launch boresighting of related elements may not be possible. Direct measurement techniques will provide alignment knowledge, or special maneuvers may be resorted to establish alignment.

Self-Calibrating -- Parameters which vary outside achievable ranges will be calibrated on line by techniques such as Kalman filters. Where on line is not practical, special self-calibrating modes will be implemented.

Adaptable to Variable Mass Properties -- The ACS will adjust to variable mass properties due to change in consumables or when docked with other platforms. The means of implementation is through robust design and adaptive control techniques.

Smart Sensors and Actuators -- ACS systems will evolve to include distributed processors associated with sensors and actuators which will better distribute function to help implement redundancy management and standardize interfaces.

Solid State Sensors -- Solid state area array sensors will complete the current trend in replacing older sensors in order to extend life and increase environmental tolerance.

Optical Components -- Where high speed computation in support of control of very large space structures requires optical computation and interfaces, that technology will be available.

High Speed Wheels -- High speed wheels with dynamic braking will be available to reduce weight and power.

Expert Systems -- Systems will be sufficiently complex to be able to provide error detection and correction function as well as to make judgements on performance levels being provided.

6.0 ANTICIPATED ACS TECHNOLOGY SHORTFALLS - 2000

Increased performance in guidance, navigation, and control systems is driven by the need for large space structures, large optical assemblies, and high precision orbit determination. The newly emerging large systems will be a synthesis of active and passive control of pointing, vibration, and surface shape. These areas have been, and will likely continue to be, the topics of much research.

Near-earth navigational performance will need improvement to reach the subdecimeter range via improved atmospheric drag and solar pressure models, and extension of geoid measurement, to cover the oceans. Special attention is needed for interplanetary spacecraft that orbit or land upon extraterrestrial bodies, in view of poorly known gravity fields, erratic atmospheric drag, etc.

Many advances in spacecraft pointing, vibration, and figure control systems are needed. Measurement systems will be improved through new techniques, such as image motion compensation, to overcome inherent performance limitations. Active figure control systems will soon become commonplace as surface accuracies decrease to the equivalent of visible wavelengths and smaller. Continual research, experimentation, and data collection is needed to fully understand the behavior of large space structures. The control techniques, sensors, and actuators will drive the need for special avionics that are equivalent to many multiples of general purpose on-board computers. The actuators needed will require extended life and capabilities well beyond their currently expected performance.

6.1 SENSORS

A key item to implementing future ACS technology will be advanced sensing systems. To a certain degree, reduction in design costs and standardization of interfaces will reduce the difficulties that may be present in implementing new systems. Incorporating autonomy into sensor systems will permit fault isolation/detection, selection of alternative redundant devices and data paths, and enable designs which have operational capabilities in multiple modes.

Many of the needs associated with improved capability, high accuracy and reduced cost lead to requirements for automation of the navigation function. Automation also lends itself to rendezvous, stationkeeping, docking, and multiple vehicle traffic control. Current requirements have driven the automation of many ground navigation functions, especially for earth-orbiting spacecraft, and future projections indicate a continued trend in this direction. In addition to ground navigation system automation, requirements are evolving which require the development of totally on-board navigation sysems and/or hybrid spacecraft/ground navigation algorithms, failure detection and correction techniques, and proximity sensors.

Increasing ACS performance requirements, both for more conventional spacecraft design and large space structures, also will require noise reduction in sensors and accuracy improvements in high precision star trackers. Improved system reliability, and possibly reduced mass, can be gained by extended lifetimes for gyros (IRUs). Lightweight, integral structural shape and vibration sensors are needed for the future. It has been estimated that the sensor/actuator system for a 500-lb flexible structure may weigh several thousand pounds. These types of devices simply do not exist in a suitable form.

6.2 PROCESSING

The processing shortfalls in ACS technology occur in two broad areas: analytical design methods and software design tools. Analytical methods must be developed to perform critical design tasks; additionally, reliable control design software must be developed to cope with high-order systems design and simultaneously handle the new design methods.

Algorithm development is required for unified ACS/structural design, adaptive structural filters and autonomous design. Shape control, shape estimation, and agile systems are also included under the unified design ACS/structural design procedures.

Software development is required for high-order/multi-rate/ multi-loop systems design. Large flexible spacecraft design is one of the main drivers of the new technology requirements.

Each of these technology areas may be defined as follows:

Unified ACS/Structural Design -- This area involves the interdependent and simultaneous design of the control system and spacecraft structure. Current design practice separates the spacecraft structural design from that of the control system; i.e., the control system is designed as an add-on. Although this procedure is satisfactory for small satellites requiring only altitude control, it is unsatisfactory for large flexible spacecraft requiring active control of the various vibration modes. A unified system design capability will allow the design of extremely lightweight structures with structural optimization procedures incorporating the control system parameters as design constraints.

Design Tools -- Computational algorithms and reliable software must be developed for high-order multi-rate/multi-loop control systems. Flexible spacecraft design will employ dynamic models of 100th order and greater.

Additionally such systems will employ many actuators and many sensors with attendant non-linearities and system noise. The slewing of flexible articulated vehicles involves an additioinal class of non-linear control problems. The complexity of these problems is beyond the state of current design software. Numerically stable software packages need to be developed that provide reliable answers for these design problems.

Adaptive Structural Filters -- Large platforms are subject to berthing, docking, and evolutionary structural modifications. To ensure stable control, adaptive filter algorithms must be developed for system identification and adaptive control. All aspects of the system require identification: mass properties, mode shapes, mode frequencies, damping, and system disturbances. As performance requirements increase, the accuracy of the model required for control design increases; the maintenance of stability and performance in the presence of large system modifications requires precise knowledge of system parameters, and adaptive structural filtering is a critical technology.

Autonomy Techniques -- Autonomous satellite operations will be required for deep space missions, long-life satellites, and emergency conditions when ground station communication is impossible.

6.3 ACTUATORS

The attitude control systems to meet the mission requirements of the year 2000 will need actuators with greater capabilities and of types not currently used in space.

The need for advanced capabilities are derived from higher accuracy autonomous operational needs of multi-payload (platform) and flexible structures. Low noise is needed for better resolution over a wider bandwidth and to reduce structural interactions. Noise sources are unbalance, bearing noise, sampling rate, and magnetic and mechanical imperfections.

A critical technology issue is wider and variable dynamic range required to provide greater accuracy, less jitter, and lighter weight by operating at higher rotational speeds with good power efficiency. The recent discovery of new magnetic materials and high efficiency power conversion techniques can be exploited to provide a new generation of attitude control devices with large systems benefits and tighter control loops. These are needed to implement ACS systems capable of adaptive control to handle "growth" requirements and permit autonomous and self-optimizing control.

A second critical technology need is for structural actuators which are devices to react forces within the structure rather than on inertial elements. They are needed for shape control (remove distortion) and active control of structural dynamics which affect pointing of multiple payloads on a common platform. These may be linear actuators rather than classical rotary devices. They can potentially raise fine pointing bandwidths from the fractional Hz cutoff of the primary ACS to approximately 100 Hz with equivalent improvements in jitter control and accuracy. These are needed to provide large multiple payload systems the same degree of (sensor limited) performance previously possible only with dedicated spacecraft and/or image motion compensation systems which are a costly penalty on each instrument. Providing active vibration control integrated into the structure can provide broadband damping to eliminate the numerous multi-mode resonant peaks characteristic of large complex lightweight structures. Piezo-electrics and shape-memory alloys offer the prospect of static shape control with minimal power. Electro-magnetic devices have sufficient bandwidth and inherent rate sensing which will minimize the distributed control system penalty. These new actuator developments are required to implement the jitter-free platforms as a precision pointing platform and reduce the need for stringent disturbance restrictions, individual isolators, and multiple gimbaled fine pointing mounts for individual instruments and payloads. They will provide a stable base for observations, science, and future narrow beam optical communication links.

Standard interfaces are needed to provide economy, reliability, and growth potential so that future systems upgrades can be made by software, servicing by direct replacement facilitated, and "growth" additions readily accommodated. Major harness weight reductions by fiber-optics and the insertion of ACS tags into payload data packets will be possible.

6.4 TEST

There is a need for attitude control engineers to have test beds to enable them to validate attitude control system perfromance. Test beds are an essential capability that permits the control engineer to confidently predict performance capability and to establish performance margins. Tools such as these are needed if reliable first flight performance is to be achieved. Often the control engineer is permitted a single opportunity to accomplish the task. Exercising simulation test beds can be an important step in the process of gaining the necessary confidence and reduces risk. Test beds are used for operational support and can be used to evaluate performance of possible growth options. They can also be essential to evaluate the viability of new applications such as autonomous control, or telerobotic/robotics, etc.

Typically, many types of test beds are utilized to gain the necessary confidence in the attitude control system design. In the ground based environment there are software development test beds to exercise operational code, a variety of mainframe computer performance simulations to validate specific phases of operation and associated performance, and hybrid simulations that employ both hardware and software for more comprehensive evaluations of performance.

In the process of developing a dynamical model for subsequent simulation purposes, the control designer usually develops an analytic model first. Typically, this model is verified experimentally by ground test. However, with the evolution in spacecraft design towards designs with multiple payloads requiring precise pointing, satellites with many modes of operation involving widely varying mass states, or satellite designs involving large structures, the feasibility of experimental verification on the ground is at issue. This is particularly true for large spacecraft that may not even be supportable in a gravity environment. Providing the necessary suppport can substantially alter the dynamics of the model to be tested. Thus testing in a zero gravity environment may be the only recourse. From a practical viewpoint, if testing in space is deemed necessary, then it might be desirable to employ subsystem scale model testing to confirm analytical models, and then extrapolate to the actual flight article. The issue of scalability can be a concern, however. The request for a space test bed anticipates the needs outlined above, and may ultimately be the only viable method to derive a validated dynamical model that can subsequently be used to extrapolate performance on orbit. As a by-product, a space test bed would have other advantages such as providing opportunities to qualify new technology in a space environment.

7.0 ACS CRITICAL TECHNOLOGY ISSUES - 2000

The ACS technology shortfalls which are enabling, not just enhancing, have been classified as critical issues. All of them can be grouped under one of the following four categories:

ACS Validation & Test -- includes the critical issues of component and subsystem modeling and test; simulation model validation; and software development/validation (which is meant to include the multi-variable, adaptive, FDC, and autonomy software).

Flexible Structure Control -- to provide dynamic and form control including structural sensors and actuators; adaptive filters/algorithms; multi-rate, multi-loop design tools; a unified ACS/Structural design approach; and variable dynamic range systems.

ACS Autonomy -- including fault detection and correction for both autonomous navigation and autonomous spacecraft operations.

ACS Sensors -- covering low noise sensors; high accuracy star trackers; and long distance proximity sensors.

8.0 RECOMMENDED ACS TECHNOLOGY PROGRAMS

The following four technology programs are recommended to address the ACS critical technology issues for spacecraft in the 21st century. A brief description of the objectives, rationale/need, approach, and payoff is provided. Time did not permit any detailed planning nor coordination with existing or planned technology programs. In general, most of the latter programs are planned to address mission unique technology needs that could, in some cases, be applicable to the spacecraft 2000 state-of-the-art. If the recommended programs are considered for implementation, the planning should include a survey of the related technology programs already planned or funded, and coordinated activity to avoid duplication in the fundamental technology issues.

The recommended programs are listed in the order of priority with the most urgent listed first. The first two programs were both considered to be of the highest priority because of their potential impact on so many different mission areas.

8.1 ACS VALIDATION & TEST PROGRAM

Objective

The objective of this program is to ensure that the Attitude Control System's hardware and software, when subjected to the orbital environment, provides the required mission performance.

Rationale/Need

The complexity of the ACS has grown considerably to recent years because of the availability of unlimited computational capability. Adaptive designs are difficult to test and require extremely accurate analytical models which have to be validated to avoid risking the mission's success. As the complexity has grown, the performance capabilities have improved beyond the current and projected test capability. The test equipment is not as accurate as the ACS sensors and truth models or references aren't available to validate performance. Ground testing involves significant test limitations due to gravity effects, earth's rotation, atmospheric effects, and environmental disturbances.

Operational support will require validated models of the ACS hardware and software to evaluate anomalies, new configurations, mission modifications, and servicing. Missions which plan on-orbit growth will have to have a method of ACS validation and test to provide the confidence that the new configuration will be stable and will meet the required performance.

Autonomous missions will require a sophisticated ACS that will be a major challenge to validate and test. A means of exercising the autonomous features prior to flight, to insure design adequacy, is needed.

Approach/Methodology

Both a ground based test bed and an on-orbit test facility should be developed particularly to serve the Attitude Control System needs.

The ground test bed would be used to not only validate the ACS software, but also to serve as a software development facility. The test bed would include a detailed digital simulation of the ACS running in a large mainframe which would interface with the ACS hardware and software under test. A hybrid capability of introducing either the actual ACS hardware or a simulation into a test would be provided. The test bed would be used for operational support to validate new configurations or software.

The space test bed would be used to provide flight qualification on ACS components and to validate ground test results and simulation models. The test scaling between ground and flight would be validated or established such that reduced scale ground tests could be used with confidence.

Payoff

Reliable first flight performance could be ensured by using these test beds. Improved ACS testing will find problems or weaknesses prior to the mission use.

New ACS technology could be qualified with no program risk. New technology is considered unproven until space qualified. Advanced hardware cannot be flown unless the related performance is urgently needed and can justify the mission risk.

The ACS performance and margins could be quantified to allow improved mission performance and growth.

8.2 FLEXIBLE STRUCTURE CONTROL PROGRAM

Objective

A systematic technology program involving sensors, actuators, design software and algorithmic development is required to meet mission objectives for the year 2000. The new spacecraft will be large, lightweight, and in most cases have flexible appendages. The large size and low mass density of these vehicles lead to many closely spaced low frequency vibration modes. This low frequency dynamic behavior coupled with stringent control requirements leads to a new class of satellite control problem.

Current design processes that place all vibration modes outside the control system bandwidth, or simply notch out an offending vibration mode, are not adequate for mission success. The new class of satellite requires more sophisticated approaches.

Rationale/Need

Some of the more challenging problems associated with large spacecraft control are as follows:

Multi-Payload Precision Pointing -- This problem occurs on large satellites with diverse payloads, each of which have stringent pointing requirements. The problem becomes one of providing precision pointing for each of the payloads and preventing destructive interference between the various payloads and the associated flexible space platform.

Pointing and Control Stability -- Precise pointing for large flexible structures calls for new design processes that provide active vibration control for the modes and pointing control for the rigid body. This will of necessity lead to high-order dynamic systems that have many actuators and many sensors; i.e., high-order, multi-input/multi-output control with many major and minor loops operating at different sampling speeds. There exists little practical design experience with such multi-loop systems.

Shape Control and Estimation -- Large spacecraft require two classes of shape control. The first class can be termed geometric or configuration control wherein various spacecraft components are maintained in a preferred alignment or configuration; i.e., each component is treated as a rigid body and aligned accordingly. Our example would be the reflector, boom, and feed orientation in an offset antenna class spacecraft. The second class of shape control involves constraining a subsystem to maintain some idealized geometric shape. An example would be shape control of a parabolic reflector. This class of shape control requires a sophisticated system of shape estimation such that correction forces can be generated in real-time. Currently there is no industrial experience base that copes with this problem. Most of the work is in the conceptual state.

Abrupt System Control -- Abrupt systems are those wherein the system parameters, dynamic order, or configuration change abruptly in step response fashion. Such changes occur during berthing and docking of spacecraft. Changes of smaller magnitude, but similar nature, occur during evolutionary growth when new elements are added to an existing space structure. Control must be maintained before, during, and after such step changes in system configuration. Currently there exists no unified approach to cope with control across such system discontinuities.

Large Agile Flexible Structures -- Agile flexible systems under going fast large angle maneuvers are another area requiring development. Work is required in both dynamics and control. Currently there exxists no way to perform the necessary computations for guidance and control in real time.

Approach

In order to correct deficiencies in the technology program are required in the following areas:

Structural Sensors & Actuators -- An extensive structural sensor and actuator program is required. Hardware development is lagging behind theory development in structural control technology. Devices that respond to low frequencies are lacking; i.e. responses from DC to 1 hertz are required. Inertial devices and devices that respond point-to-point within the structure are required. Structural shape sensors and actuators do not exist at this time. Low frequency vibration control devices tend to be bulky and cumbersome; i.e., a typical proof-mass actuators currently available for operation at 0.12 Hertz weigh approximately 70 lbs. The lack of available hardware for control structure interaction (CSI) technology forms a critical block. The most elegant scheme cannot function without proper sensors and actuators.

Design Tools -- A computer software program is required for estimation and control algorithm development. A specific lack exists in software for high-order systems design required for structural control.

Unified Structural/ACS Design -- Methodology and algorithms must be developed that allow unified design of both the structure and control system. This process ensures maximum use of structural mass and control capability and represents the next step toward a mature active structural control capability.

Real Time Alignment Transfer -- The precision pointing of multiple payloads from large space platforms calls for the development of real time attitude reference transfer systems. The technology is necessary if large space platforms are to perform their missions.

Payoff

The vigorous development of technology for flexible structure control will ensure the use of large lightweight structures with improved pointing capability and enable stable control of evolutionary structures. The payoff to the nation's space program in terms of increased capability and reduced development costs is tremendous.

8.3 ACS AUTONOMY PROGRAM

Objective

The objective of this program is to eliminate or minimize the ground support operations. The ground support manpower costs associated with long-life spacecraft can be the major cost element depending upon the level of ACS autonomy. An autonomous ACS will also maximize the mission return by avoiding or minimizing downtime due to equipment failures.

Rationale/Need

The ever-increasing complexity of spacecraft ACS has increased both the quantity and quality of ground support required to ensure continuing on-orbit performance. Critical timelines can necessitate multi-shifts and numerous ground stations. Limited ground station coverage and availability also dictates minimum ACS autonomy for future spacecraft. An autonomous ACS and navigation system helps satisfy the need for attitude data and ephemeris data for on-board payload use. The immediate availability of such data to the payload is needed in many missions.

Approach/Methodology

An autonomous fault detection and correction system would be developed to establish when an ACS element has failed, to establish the optimum replacement policy, and to implement the replacement without ground assistance. This would build upon the automatic control modes already provided in many of today's systems.

An autonomous navigation system would be developed to provide ephemeris data on-board without the need for ground tracking nor uplinked data. It will interface with the autonomous ACS to provide extended periods of independent spacecraft operation.

Artificial intelligence techniques, extending the expert systems expected in the immediate future, will be used to replace extraordinary ground support functions.

Payoff

High availability is the ultimate payoff. Safe reconfigurations of the ACS will be provided avoiding any potential ground command errors. The TT&C bandwidths, supporting the ACS and payload telemetry and commands, could be reduced since data need not be interchanged with the ground. Life cycle costs would be significantly reduced for long-life spacecraft. The ephemeris accuracy for an autonomous system would in most cases be more accurate than ground generated with on-board reconstruction. An autonomous ACS would make the spacecraft more survivable in the event of war because ground dependency would be eliminated.

8.4 ACS SENSORS PROGRAM

Objective

The objective of this program is to develop the technology for low noise attitude sensors, to develop a high accuracy star tracker, and to develop a long distance proximity sensor.

Rationale/Need

Low noise sensors and high accuracy star trackers are needed to enable spacecraft to perform precision pointing missions. With unlimited computational capabilities, the limiting item for pointing accuracy is the sensors. Rendesvous and docking requirements will be more commonplace for the 21st century spacecraft in order to facilitate servicing, repair, and reconfiguration. An accurate long distance proximity or ranging sensor with general applicability is needed.

Approach/Methodology

The approach would be to develop improved image motion compensation techniques, to explore fiber optic and other advanced rate sensing instruments, and to apply payload sensor technology advances to the ACS sensing approaches. A three axis solid state star tracker would be developed to provide sub arc second accuracies. A long distance range/orientation sensing system would be developed to address the anticipated rendezvous and docking needs.

Payoff

This program would result in improved payload performance, improved attitude reference data, longer life spacecraft, and would provide a critical component for an autonomous navigation system. It would enable automatic rendezvous and docking.

APPENDIX A

SPACECRAFT 2000
ATTITUDE CONTROL

- WORKING GROUP MEMBERSHIP
- REQUIREMENTS - 2000
- CONSTRAINTS - 2000
- PREDICTED TECHNOLOGY STATUS - 2000
- TECHNOLOGY SHORTFALLS
    - SENSORS
    - PROCESSING
    - ACTUATORS
    - TEST
- ACS CRITICAL TECHNOLOGIES
- RECOMMENDED TECHNOLOGY PROGRAMS
    - ACS VALIDATION & TEST
    - FLEXIBLE STRUCTURE CONTROL
    - ACS AUTONOMY
    - ACS SENSORS

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ACS REQUIREMENTS - 2000

- INCREASED BANDWIDTHS
- MICRO G PERFORMANCE
- MODULAR
- REPLACEABLE
- SERVICEABLE
- HIGH ACCURACY
- FAULT TOLERANT
- HIGH RELIABILITY
- LONG LIFE
- TORQUE/MOMENTUM GROWTH CAPABILITY
- MINIMUM WEIGHT
- AUTONOMOUS
- ROBUST
- ADAPTIVE
- MANUEVERABLE/AGILE
- LOW JITTER
- PAYLOAD SENSOR CONTROL CAPABILITY
- SEU/RADIATION TRANSIENT IMMUNITY
- MULTIPLE PAYLOAD POINTING

ACS CONSTRAINTS - 2000

COMPONENT

- LOW COST
- NONOPTIMAL
- DEMONSTRATED/QUALIFED
- LIMITED FOV

SUBSYSTEM

- LARGE FLEXIBLE STRUCTURES
- VARIABLE MASS PROPERTIES
- LIMITED PREFLIGHT TESTING
- ALIGNMENT TRANSFERS
- DISTRIBUTED COMPONENTS
- RADIATOR POINTING LIMITATIONS
- UNCOMPENSATED MOMENTUM
- CREW SAFETY

PREDICTED ACS TECHNOLOGY - 2000

- MULTI-MODE REPROGRAMMABLE
- SELF-ALIGNING
- SELF-CALIBRATING
- ADAPTABLE TO VARIABLE MASS PROPERTIES
- SMART SENSORS & ACTUATORS
- SOLID STATE SENSORS
- OPTICAL COMPONENTS (PROCESSING)
- HIGH SPEED WHEELS
- EXPERT SYSTEMS

ACS TECHNOLOGY SHORTFALLS - 2000

SENSORS:

- AUTONOMY
- • LOW NOISE SENSORS (M)
- LONG LIFE GRYOS
- LOW COST DESIGN
- STANDARD INTERFACES
- MULTI-MODE SENSORS
- • HIGH ACCURACY STAR TRACKERS (M)
- • STRUCTURAL SENSORS
- • AUTONOMOUS NAVIGATION (M)
- • PROXIMITY SENSORS (M)

• - CRITICAL OR ENABLING TECHNOLOGY
(M) - POSSIBLY MISSION UNIQUE/DEPENDENT

PROCESSING:

- • UNIFIED ACS/STRUCTURAL DESIGN METHODS
- • DESIGN TOOLS FOR HIGH-ORDER MULTI-RATE/MULTI-LOOP SYSTEMS
- • ADAPTIVE STRUCTURAL FILTERS FOR CONTROL AND ESTIMATION
- • AUTONOMY TECHNIQUES
- LOW COST DESIGN METHODS
- STANDARD INTERFACES

ACTUATORS:

- LOW NOISE ACTUATORS
- • VARIABLE DYNAMIC RANGE
- • STRUCTURAL ACTUATORS
- STANDARD INTERFACES

ACS TECHNOLOGY SHORTFALLS - 2000

TEST:

- HARDWARE COMPONENT MODEL VERIFICATION
- *CONTROL ALGORITHM ASSESSMENT
- *SOFTWARE VALIDATION
- *ZERO G MODEL VERIFICATION
- *SOFTWARE/HARDWARE SUBSYSTEM PERFORMANCE PREDICTION USING VALIDATED SIMULATIONS
- *SCALING VALIDATION
- OPERATIONS SUPPORT
- FDI/AUTONOMY/AI VALIDATION
- *COST EFFECTIVE EVALUATION

ACS CRITICAL TECHNOLOGIES

1. ACS VALIDATION & TEST
   - COMPONENT AND SUBSYSTEM MODELLING AND TEST
   - SIMULATION MODEL VALIDATION
   - SOFTWARE DEVELOPMENT/VALIDATION (MULTI-VARIABLE, ADAPTIVE, FDC, AUTONOMY)
2. FLEXIBLE STRUCTURE CONTROL (DYNAMIC & FORM)
   - STRUCTURAL SENSORS & ACTUATORS
   - ADAPTIVE FILTERS/ALGORITHMS
   - MULTI-RATE, MULTI-LOOP DESIGN TOOLS
   - ACS/STRUCTURAL UNIFIED DESIGN
   - VARIABLE DYNAMIC RANGE SYSTEMS
3. ACS AUTONOMY
   - AUTONOMOUS OPERATIONS/NAVIGATION
   - FAULT DETECTION & CORRECTION
4. ACS SENSORS
   - LOW NOISE SENSORS
   - HIGH ACCURACY STAR TRACKER
   - PROXIMITY SENSORS

I. TECHNOLOGY PROGRAM - ACS VALIDATION & TEST

OBJECTIVE:

- VALIDATE ACS PERFORMANCE
  - SOFTWARE
  - HARDWARE

RATIONALE/NEED:

- ACCURATE MODELS FOR COMPLEX ADAPTIVE DESIGNS
- PERFORMANCE INCREASE BEYOND TEST CAPABILITY
- GROUND TEST LIMITATIONS
- OPERATIONAL SUPPORT
- GROWTH VALIDATION
- AUTONOMY VALIDATION

APPROACH/METHODOLOGY:

- DEVELOP A GROUND TEST BED
  - SOFTWARE DEVELOPMENT
  - MAINFRAME PERFORMANCE SIMULATION
  - HYBRID SIMULATION CAPABILITY
- SPACE TEST BED
  - FLIGHT QUALIFICATION
  - ZERO & MODEL VALIDATION
  - SCALING VALIDATION

PAYOFF:

- RELIABLE FIRST FLIGHT PERFORMANCE
- QUALIFIES NEW TECHNOLOGY
- QUANTIFY PERFORMANCE CAPABILITY/MARGIN
- COST/RISK REDUCTION

II. TECHNOLOGY PROGRAM - FLEXIBLE STRUCTURE CONTROL

OBJECTIVE:

- STABLE CONTROL OF LARGE FLEXIBLE SPACECRAFT
- SHAPE CONTROL OF LARGE SPACECRAFT APPENDAGES

RATIONALE/NEED:

- MULTI-PAYLOAD PRECISION POINTING
- POINTING STABILITY/CONTROL STABILITY
- SHAPE CONTROL
- ABRUPT CONFIGURATION CHANGE
- LARGE AGILE FLEXIBLE SYSTEMS

APPROACH/METHODOLOBY:

- DEVELOP STRUCTURAL SENSORS AND ACTUATORS
- DEVELOP DESIGN TOOLS
- DEVELOP UNIFIED STRUCTURAL/ACS DESIGN METHODS
- DEVELOP REAL-TIME ALIGNMENT TRANSFER TECHNIQUES

PAYOFF:

- ALLOWS LIGHT WEIGHT LARGE STRUCTURES
- IMPROVED PRECISION POINTING OF FLEXIBLE STRUCTURES
- STABLE CONTROL OF EVOLUTIONARY STRUCTURES
- REDUCED DEVELOPMENT COSTS
- APPLICABLE TO MULTI-AXIS ROBOTIC CONTROL

III. TECHNOLOGY PROGRAM - ACS AUTONOMY

OBJECTIVE:

- REDUCE GROUND SUPPORT OPERATIONS (MANPOWER/COST)
- MAXIMIZE MISSION RETURN

RATIONALE/NEED:

- INCREASED ACS COMPLEXITY/SUPPORT
- CRITICAL TIMELINES
- LIMITED GROUND STATION AVAILABILITY
- ACS/PAYLOAD DATA CORRELATION

APPROACH/METHODOLOGY:

- DEVELOP AUTONOMOUS FAULT DETECTION DETECTION & CORRECTION SYSTEM
- DEVELOP AUTONOMOUS NAVIGATION SYSTEM
- USE AI AS APPLICABLE

PAYOFF:

- HIGH AVAILABILITY
- SAFE ACS RECONFIGURATION
- REDUCES TT&C BANDWIDTH
- REDUCES LIFE CYCLE COSTS
- IMPROVED EPHEMERIS ACCURACY
- IMPROVED SURVIVABILITY

IV. TECHNOLOGY PROGRAM - ACS SENSORS

OBJECTIVE:

- DEVELOP:
  - LOW NOISE SENSORS
  - HIGH ACCURACY STAR TRACKER
  - PROXIMITY SENSOR

RATIONALE/NEED:

- PRECISION POINTING MISSIONS
- RENDEZVOUS & DOCKING

APPROACH/METHODOLOGY:

- DEVELOP 3-AXIS SOLID STATE STAR TRACKER
- DEVELOP IMPROVED IMC
- EXPLORE FIBER OPTIC AND ADVANCED RATE SENSORS
- DEVELOP LONG DISTANCE RANGE/ORIENTATION MEASUREMENT SENSOR

PAYOFF:

- IMPROVED PAYLOAD PERFORMANCE
- IMPROVED ATTITUDE REFERENCE
- LONGER LIFE
- CRITICAL AUTO NAV COMPONENT
- AUTOMATIC RENDEZVOUS & DOCKING

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APPENDIX B

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